The Report committee for Mariel Elizabeth Kerbacher

Certifies that this is the approved version of the following report:

Thermal Mass Applications in the Hot-Humid Region of Austin, TX

APPROVED BY

SUPERVISING COMMITTEE:

Supervisor: ____________________________________

Atila Novoselac

____

Ying Xu

Thermal Mass Applications in the Hot-Humid Region of Austin, TX

by

Mariel Elizabeth Kerbacher, B.A.

Report

Presented to the Faculty of the Graduate School

of the University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

December 2010

Thermal Mass Applications in the Hot-Humid Region of Austin, TX

by

Mariel Elizabeth Kerbacher, MSE

The University of Texas at Austin, 2010

SUPERVISOR: Atila Novoselac

Thermal mass can be successfully implemented in the hot-humid region of Austin, TX especially when well-designed and with supplementary aids like night-cooling and day-lighting. This study shows that in some situations thermal mass can be actually more beneficial at reducing electricity demands in hot-humid regions than in the hot-dry regions that are so emphasized in the literature.

Table of Contents

List of Tables and Figures

OVERVIEW AND INTRODUCTION

Energy consumption has become a major problem in this country, especially in the building sector. Buildings in the US consume about 39% of the energy used nationally (42% of that from heating and cooling) [DOE-EERE, 2009], which is equivalent to 1/5th of the energy used globally each year [DOE-EIA, 2010]. As unfortunate as this is, it presents a major opportunity to use purposeful design to decrease the energy consumed by buildings. The sector of small commercial buildings is a good place to investigate, because this area is developing the interest and has the resources to invest in more sustainable buildings. Also, it comprises a large percentage of the building energy usage in the US, therefore improving this particular sector's energy efficiency could have a large impact overall.

Scientific literature provides an understanding of the physics behind and the use of thermal mass. Many papers are concerned with applications of thermal inertia in hot-dry climates but much fewer consider hot-humid climates, such as the climate zone for Austin, Texas. Of the few papers that mention this region, most simply state that the technique is not very useful but did not go on to explain this claim. However, Al-Homoud, 2005, states that in humid climates good insulation can make a bigger impact on thermal comfort than thermal mass due to smaller variations in daily temperature highs and lows. The objective of this study is to investigate thermal mass applications in Austin, Texas by researching the current scientific literature and by utilizing eQUEST modeling software to determine if there is an ideal implementation of thermal mass that could be of benefit in this region. The optimized thermal mass model for Austin is be compared with the same building model in the postulated "more successful" hot-dry region of Phoenix, Arizona to identify the amount of potential usefulness of thermal mass in this area measured against the outcomes in other climate generally will define regional imperatives.

eQUEST is an example of a response function building energy modeling software. It assumes a one dimensional heat transfer perpendicular through surfaces and approximates with the lumped node analysis method where all across each surface the temperature is considered constant [eQUEST, 2007]. It is selected as the modeling tool for this project due to its relatively quick learning curve and ease-of-use with respect to the quality of data that is generated. Because it was originally developed by the Department of Energy the output is considered very reliable as long as the parameters are defined correctly. eQUEST can use the data about energy savings to do economic analysis of changes in the thermal mass situations. It is also a free-software downloadable from the DOE website [http://doe2.com/equest/]

The literature review consists of a general definition and purpose of thermal mass, and the indoor effects of using thermal mass, along with various implementation strategies including pre-cooling, the placement, and orientation in design. This is followed by a brief history of thermal mass applications and types of applications common today, considering in particular the importance of regional specialization and a return to the "basics" in many areas, as well as the push for technological innovations currently being researched. Overall it is determined that thermal mass saves a significant amount of energy as well as money in the operational costs of the building. This optimum however does vary depending on the source of the data. "The effectiveness of thermal mass for reducing summertime overheating has been well established for both domestic and commercial buildings [Palmer et al., 2005]." This also follows for the substantial difference thermal mass makes on wintertime passive heating. Finally, the literature research specific for hot-humid regions is presented, leading into the eQUEST modeling and results.

In this study a baseline building model is constructed for the Austin, TX climate region and the eQUEST wall parameters are varied until an optimum power saving design is found. Additional techniques are investigated that work to improve the thermal mass performance including: day-lighting, night-cooling, and shading, then the best of these designs for the Austin region is compared with that same design's performance in Phoenix, AZ. This is not a perfect way of comparing the locations because a good design in one climate usually cannot work as well in another climate without modifications and here there are no modifications of the design across the regions. This is the best way to show how the basic impact of thermal mass affects electricity power savings in both climates compared with Austin's data.

An outcome of this report is a compilation and analysis of scientific literature about thermal mass and data gained from modeling possible applications of thermal mass in Austin. It is important to determine how thermal mass functions in hot-humid regions like Austin, TX because thermal mass has been shown to be a very successful building design strategy for reducing energy consumption (and costs) in hot-dry climates and could be of potential importance in others as well. Thermal mass absorbs heat from a space during the warm day and releases it when the temperature drops below that which it has stored, such as in a cool night. It works best in locations with great daily extremes in temperature but it has been suggested that high humidity reduces these swings and thus reduces the effectiveness of the massive material. A goal of this report is to gain realistic data from eQUEST about the amount of power that could be saved through the incorporation of thermal mass on a design in Austin. If thermal inertia is found to function well in this region there are great implications for implementing it in this area because of Austin's propensity towards the "Green."

LITERATURE REVIEW

The United States is one of the wealthiest nations in the world and the national culture tends to favor immediate results even at high costs. This tendency is also reflected in building thermal comfort. When it's 90° F outside a person may want it to be 65° F indoors just because the technology allows it and that's what they understand that it should be. The operational energy use of the average American home is dominated by 50-70% for heating and cooling alone [DOE, 2002]. These same people are generally resistant to changing their ways unless it proves somehow beneficial to themselves. Along such lines of thought when their air-conditioner breaks they need it fixed now, and if it keeps breaking due to misuse many people still want a newer, better one that can produce the desired comfort in the building even at the expense of wasted energy and resources. It is proposed that the overall concept of building comfort needs to be rethought and integrated into the initial designs of the building itself rather than seen as a separate system. This is true for commercial as well as residential buildings.

THERMAL MASS DEFINITION

The use of thermal mass, or thermal inertia, is one way to accomplish this. Thermal inertia is the naturally occurring effect of heat accumulation and storage generally in high-mass, high-density materials during warm periods and consequently its release during cooler periods. Heat travels from warmer to cool areas. This flow of heat through a material is called conduction. Convection is the transfer of energy to and from surfaces due to the natural or forced air movement along the surface. Radiation is the transport of energy from one body to another cooler body though air or empty space. It is driven by the thermal gradient. Thermal masses utilize all of these heat transfer mechanisms to function and as the sun warms the air (or a wall) the air becomes warmer than masses still cool from the night. These masses absorb some of the heat out of the air slowing down the overall accumulation of heat in a room so that the hottest points in the day and in the room no longer coincide (this is called peak or load-shifting). As the daytime temperature reaches its peak, the mass continues to intake heat energy and as the day reaches its end and begins to cool down again, the storage capacity of the mass is reached. Later in the evening the warmer mass begins to discharge heat energy into the cooler night air, effectively and naturally warming the building at night and cooling it during the day. In this way the internal temperature trend is delayed and even reduced from that of the external air temperature.

Sometimes this process is described from a cooling perspective in terms of coolth. Coolth means the absence of heat. In essence coolth is the amount of emptiness in a material available for heat energy to fill. It is simply another way of viewing the transfer of heat into an object as spreading coolth instead of absorbing heat. It is to be noted that when the material is said to store heat (or coolth) that doesn't mean that the energy is absorbed and leaves the system, it simply means that the energy is stored and released again over a period of time. The same amount of total energy is transferred but over a different time span. The extent of this effect is determined by many factors including the amount of thermal mass available, the surface area, the air movement, and the amount and intensity of the energy that the thermal mass is exposed to. It has been stated by Ogoli, 2003, that high mass buildings can display up to a 5 hour delay in the internal temperature peak. The high mass building in his study incorporated 200 mm (~8") thick stone external walls. Pre-cooling is commonly used in conjunction with thermal mass to enhance its effects. Pre-cooling is the process of cooling down a building during unoccupied times, usually in the night, to in effect purge the heat out of the walls so the thermal mass can be used afresh the next day when the occupants arrive. Pre-cooling could refer to bringing in cooler outdoor air during the night or it could mean blasting the building with AC to shift the electrical consumption loads to more off-peak times. Night-ventilation is a pre-cooling strategy that specifically uses the former method.

The focus in this paper is on thermal inertial benefits in warm climates which are primarily dominated by cooling loads. Therefore, it should be assumed that a reference has performed the study in a cooling load environment unless otherwise specified. Also, in general the term thermal mass will apply to a massive material and the term thermal inertia will refer to the strategy of implementing thermal mass to dampen and shift energy loads.

The properties of a material, both intrinsic and extrinsic, as well as the geometry and external factors can affect a material's potential to exhibit desirable thermal mass behavior. The amount of mass in a building envelope, (particularly of cementitious material or soil) directly affects the thermal storage capacity of the building [Marra, 2006]. Consequently, with greater building mass more energy is needed to change the internal temperature within the building. Therefore, high mass buildings are much less susceptible to fluxes in the external temperature than are low mass buildings. The indoor temperature of light-weight buildings is much more dependent on the outdoor air temperature and it closely follows the external temperature throughout the day. This direct relationship is unfavorable in extreme climates but the effect can be reduced in climates with large daily temperature extremes by the proper use of thermal mass techniques. Thermal mass is most effective in areas with large daily temperature extremes because the internal average temperature of a building with high thermal mass is more or less the external average temperature for the past 24 hour time period. If the climate is hot all the time, a room with thermal mass would naturally be hotter. In contrast, in climates where the night temperature drops sharply the average internal temperature in a room with thermal mass is lowered, resulting in a more comfortable temperature throughout the day and night than would be in a very light-weight structure. Ogoli, 2003, supports this and defines an equation for the maximum indoor temperature of a room based on the external daily high and low: $T_{max,in} = T_{max,out} - 0.488(T_{max,out} - T_{min,out}) + 2.44$ for closed test chambers in the climate of “equatorial high altitudes.” Other specific formulas were presented for Australia and India by Drysdale, 1976, and Raychaudhury and Chadhury, 1961, respectively.

Thermal mass has been found to work well in climates with a large daily temperature gradient, yet it is less effective in times of annual extremes as in midwinter or midsummer. During these times the thermal mass material becomes “saturated” with either heat or coolth and doesn’t function effectively as there is little temperature difference to allow a path for the heat to follow. Ideally, the thermal mass would be allowed to store and discharge heat in a cyclic fashion throughout the day to moderate the temperature in a building, but it does this best when there is a major daily variation in temperature to allow for the positive and negative heat flow paths [Marra, 2006]. “Essentially the mass acts as a thermal flywheel and can both attenuate external energy flows and suppress internal environmental energy swings” [Russell and Surendran, 2001].

Thermal mass in residences, where concrete walls generally are less than 1 meter thick, is most useful for diurnal cycles and in general is not functional in storing and releasing heat through seasonal cycles (i.e. releasing summer heat in the wintertime). In order to do this an extensive amount of thermal inertial material is needed— with walls containing concrete exceeding 3 meters thick [Marra, 2006]. Also, thermal aquifers have been suggested to store heat seasonally in groundwater with water-saturated sand or gravel. For each change in temperature of 10 K, around 3 MJ of heat energy could be stored in a 10^5 m^3 aquifer [Hasnain, 1998].

The decrement factor mentioned in Gregory et al., 2008, can be used to compare the heat capturing effect of different materials. A decrement factor is a material property that indicates the way the value of internal temperature is dampened from the external temperature. Here the decrement factor is the fraction of the average daily temperature inside the room less the desired room temperature divided by the average daily exterior temperature less the desired room temperature. Also, it is described in Aste et al., 2009, as the thermal admittance ($W/m^2 K$) divided by the thermal transmittance through the wall ($W/m^2 K$). The thermal transmittance (or U-value) is the rate heat energy flows (W) through a unit area of material (m^2) with surfaces that have a unit temperature difference of 1 K [Al-Homoud, 2005]. Thermal admittance describes the tendency of a material to release heat energy to a surrounding area. In this case the decrement factor describes the dampening of energy traveling through a material until its release.

FACTORS THAT AFFECT THERMAL INERTIA

Building orientation, window placement, thermal mass positioning, and type all play key roles in the effectiveness of the thermal mass to temper the inside climate. External conditions also greatly affect the internal temperature of a building. Barmpas et al., 2009, points out how the cooling process of the envelope is affected by the temperature, direction and velocity of external wind and also how "hot-spots" can be created near a leading edge and below the re-circulation zone of the roof of a building due to non-uniform heat transfer coefficients. These areas also affect the heat transfer into the building envelope because the temperature difference would be greater there than in other areas of the wall (assuming warm weather). As mentioned before, the size of the external daily temperature swing greatly influences the success of the thermal inertia of a building, but the thermal mass behavior can also be affected by the swings in relative humidity during a 24 hour period. Henze et al., 2007, notes that when the diurnal temperature swing is large the relative humidity can be a determining factor as to the success of the thermal mass application because humidity increases latent ventilations loads. This is with respect to his experiment analyzing the effects of pre-cooling on utility cost savings with thermal mass. Henze saw an increase of 20-30% operational cost savings due to enhanced temperature swings but a decrease of 4% of the savings with greater relative humidity swings from the reference case. These effects of both weather parameters can be summed together to see the final result of how large temperature and relative humidity swings affect individual thermal mass situations. The humidity however, doesn't seem to influence the behavior of the mass itself in this situation but rather the work done by the HVAC systems which must remove the moisture from the air to improve the thermal comfort within the room.

The path of the sun and orientation of the building can also make a difference in the overall thermal performance of the building. Barmpas et al., 2009, has classified the way the different walls of a building receive solar radiation. He points out that the east wall is the first to peak in temperature and the first to begin releasing heat energy each day. The roof is the surface that reaches the highest temperature since it is exposed to direct sunlight for the longest portion of each day. The floor and the northern walls experience temperature drops throughout the day (release of heat energy) and the western wall initial releases heat energy before gaining heat energy in the afternoon. From these patterns it is evident that the desired cooling or heating effects can be achieved though well thought-out placement of thermal mass walls. Thermal mass to the east releases heat in the afternoon but thermal mass to the west absorbs heat in the afternoon and releases it at night. In a warming climate a more massive east wall might be better, but in a cooling climate the western wall would do better massive. In each of these cases selecting the opposite wall would have detrimental effects on the building space conditioning loads. Taylor and Luther, 2004, show similar findings in their study involving both internal and external walls in a commercial building in the Riverina area of NSW Australia. They saw that the exterior south wall, and the interior north and west walls absorb heat during the middle of the day and afternoon and release it throughout the night—effectively cooling the building during working hours. Night ventilation and conduction via temperature gradient direct the nighttime heat loss outdoors. The floor and ceiling also absorbed heat throughout the day, assisting in cooling the building. It is noted that the exterior east wall released as much heat during the afternoon as that gained by infiltration but the internal west wall fortuitously absorbed that same amount. Taylor and Luther revealed that the east wall effectively slowed the transfer of the early morning heat energy into the internal surface of the building until evening time, which highlights the benefits of thermal mass over light-weight construction.

Certain authors have detailed specific wall geometries that make the most efficient use of thermal mass in buildings in the Northern Hemisphere. Al-Homoud, 2005, points out that because a north exterior wall has such little heat gain comparatively, there is not much benefit to using thermal mass on that wall. Because the peak outdoor temperature is in the afternoon, the author indicates the importance of avoiding adding to this load with thermal mass on the eastern wall that would be releasing heat at that time. He suggests altering the amount of thermal mass on the east wall to an extent that its time lag would exceed 14 hours, or conversely to use no thermal mass on that wall (and great amounts of insulation). The second case will result in heat gains through the wall but they would be in the morning rather than the afternoon. Also the roof, exposed throughout the entire day, could benefit from a very large amount of thermal mass, or very little with much insulation instead since the construction of the former would be impractical. The key again is to avoid the release of heat during the overall peak temperature of the day. It is accepted that both the southern and western walls would suffice to have a medium-weight of thermal mass so that they delay the heat gain into the building by around 8 hours. Taylor and Luther, 2004, find in their study of a small commercial building employing rammed earth external walls that the eastern external wall acts to warm the office during the middle of the day, but the south wall has a cooling effect during the day and afternoon, releasing heat later at night especially through the night ventilation.

Thermal mass restricts the influence of external temperatures while simultaneously providing a “heat sink” for internal loads. Internal mass (that within the envelope of a building) makes the most difference on internal loads and external (or envelope) mass absorbs internal loads and exterior loads entering the building. Thermal mass in external walls tends to release heat to the atmosphere at night because of the higher surface temperatures on the outer side of a wall after exposure to solar radiation throughout the day [Yilmaz, 2007].

The positive effects of thermal mass can be enhanced substantially with the proper use of insulation in the wall also. Comparing simply designed structures, light construction is found to be the most energy inefficient in hot regions and massive buildings with an outer layer of insulation conserves the most energy relatively [Aste et al., 2009]. This energy demand difference between wall models is more exacerbated in the heating season over the cooling season by an order of 10. The light-weight situation uses almost 10% more energy for heating and only about 1% more energy for cooling, according to the simulations by Aste et al., 2009. The design of the wall with the insulation on the exterior and the massive element on the room-side is successful because it encourages the uniting of the envelope with the internal environment to promote the effects of thermal mass. When this is achieved the envelope, through thermal inertia, is able have a cooling effect by both convection and radiation of heat energy [Russell and Surendran, 2001]. Chiras, 2002, also advises that the use and position of slab insulation depends on the climate. In colder environments insulation can prevent a great amount of heat loss from the interior of the building to the ground by providing a thermal break for the flow of heat, however in hot climates this is desired to cool the building, thus slab insulation may even be detrimental. This is determined by the main annual conditioning loads of the building. Also, Marra, 2006, reiterates the great improvement in thermal mass performance due to the addition of some type of insulation material.

Insulation on roofs is more important than on walls because it is exposed throughout the day. Insulation is more important in areas of great exposure [Al-Homoud, 2005]. Good insulation is more vital in regions with small daily temperature variations but large seasonal swings, whereas thermal mass is best in regions with large daily temperature swings (though some exterior insulation is beneficial here too) [Al-Homoud, 2005].

DYNAMIC MATERIAL PROPERTIES

The diffusivity, effusivity and conductivity all play key roles in the thermal storage capability of a material. The volumetric heat capacity is the change in temperature of a certain volume of material per change in energy. The diffusivity of a material is the conductivity divided by the volumetric heat capacity and it is related to the way energy travels through the material. The effusivity is the square root of the conductivity times the volumetric heat capacity and it pertains to the release of stored heat energy in a material. A larger diffusivity and larger effusivity indicate a faster heat exchange and higher heat storage, respectively. Therefore for thermal inertia it is favorable to have a material with a lower diffusivity and a higher effusivity. Increasing the conductivity (or k-value) of a material compromises the insulating potential of a material but increases the effusivity and greatly increases the diffusivity which leads to more heat storage capacity and more time delay of the peak temperature (Barmpas et al., 2009). This is why thermal mass can be successful even when it seems to not meet certain building codes due to its conductivity [Yilmaz, 2007]. High specific heat capacity (c_p) and high mass both improve the performance of materials to strengthen thermal inertia behavior [Henze et al., 2007]. A high specific heat means the material has a huge storage potential for absorbing heat energy. Water, concrete, and soil are some such materials. The range of specific heat common for building materials is from 0.8–1.8 kJ/kg K [Henze et al., 2007]. Also, the quantity of mass can affect thermal inertia greatly—by increasing the density of a material or the thickness of a wall (up to a certain extent) the thermal storage effect will be enhanced.

It is important to note the relationship of absorptance (α), transmittance (τ), and reflectance (ρ) and their impact on the way a material reacts to wavelengths of heat energy. The absorptance of a material indicates the ability of radiation energy to pass into the material surface and "be collected" in the material. The reflectance depends on the color and the shininess of a material and refers to its ability to bounce back energy rather than absorb it. Long wave and short wave radiation may strike a material and some of it may be reflected back (ρ) as long-wave radiation, while some is absorbed (α) as long-wave radiation and some is transmitted through the material (τ) as short wave radiation. For a given material this relationship holds: $\alpha + \tau + \rho = 1$. However, certain materials have specific properties. For instance, there is no transmittance through opaque materials (like thermal mass materials) so the $\tau = 0$ and light-colored or reflective materials have a greater value for ρ and thus lower absorptance and transmittance [Al-Homoud, 2005]. This surface physics indicates that if there is concern of too much heat gained into thermal mass from direct solar radiation, painting the surface white or with a gloss could lower the risk of overheating while making it a darker color can increase the absorptivity.

Overall, optimizing the thermal inertia qualities of a wall successfully depends on controlling the dynamic properties. The thermal transmittance, admittance, decrement factor, and time lag are each important but it is not necessarily the best individual values of these that would produce the optimal results. To optimize the thermal mass behaviors the whole set of dynamic properties together must be controlled to produce the most advantageous results. These geometric and surface properties show how the thermal inertia effected by the specific physical properties of a material (thus material selection and placement) can substantially affect the practicality of using thermal mass. This has been shown in numerous studies with real materials as follows.

EFFECTIVE USE OF THERMAL MASS

The selection and treatment of a thermal mass material can greatly enhance or negate the energy saving effects associated with utilizing thermal inertia. In a study by Gregory et al., 2008, it is found that the reverse brick veneer walling system performs much better as thermal mass than conventional cavity brick, brick veneer, and light-weight walling systems. The term reverse brick veneer refers to a brick veneer on the internal side of the wall, with studs and insulation on the exterior. The outer insulation with inner thermal mass is what results in the success of this system. When insulation is on the exterior it dampens the external temperature extremes that meet the wall. These dampened extremes are absorbed into the mass portion to be released into the room when the interior temperature drops below that of the heated wall. However, insulation on the exterior is more prone to damage due to exposure and when insulation gets wet its insulative properties decrease drastically [Al-Homoud, 2005]. The interior mass can similarly absorb heat generated within the building to release at a later time. If the insulation were on the inner side of the wall, then it would act more like an oven and heat generated inside would be increasingly trapped in the room. These results are also supported by Aste et al., 2009.

Many variables can be seen to improve thermal mass effectiveness in hot climates but also to minimize its effects in colder climates [Aste et al., 2009]. Increasing the ventilation rate and using shading devices are both shown to reduce energy consumption in the summer while increasing it in the winter, indicating that a standard method cannot be established for all situations to optimize the energy efficiency of a building. Ogoli, 2003, shows also that night ventilation is especially useful for improving the effects of thermal mass in warmer climates. Henze, 2005, describes the success of pre-cooling in cost-optimized and energy-optimized cases and the author notes four major beneficial effects to utilizing pre-cooling: reducing the costs from demand; savings due to paying off-peak rather than on-peak energy rates; the lesser necessity of cooling the air with lower nighttime temps; and the improved COP of the mechanical systems when operated during a cooler night.

The study by Henze et al., 2007, shows that the noontime cooling load (energy) of a building can be dropped by 15% simply by doubling the mass of the building and this load can be cut by ~24% when quadrupling the thermal mass. Strangely however, he finds that the absolute cost savings was maximized for the regular case of thermal mass thickness (4 inches massive material on the exterior wall) or half of that (2 inches massive material) over the 16 inch (4 times) case where the savings no longer outweigh the costs for load shifting. It is also noted that building pre-cooling improves the benefits of thermal mass in general and very massive buildings can do well with morning-time pre-cooling alone. The more massive the structure, the less pre-cooling is actually needed because thicker mass has greater capacity to hold heat and it requires a greater change in temperature to release that heat energy. This validates how just morning pre-cooling can be sufficient for larger mass cases. However, improper pre-cooling could lead to higher operating costs than conventional cooling [Henze et al., 2007].

Various properties of concrete used for thermal mass can be altered to improve results. One variation is the inclusion of air cavities within the wall. The physics and numerics behind the addition of vertical cylindrical air cavities in concrete walls is discussed in Zhang and Wachenfeldt, 2009, and a method for simulating actual hollow-cored slabs is suggested. The process behind the benefits of air cavities has to do with the fact that the total amount of heat that can be stored in a material depends on the access of the energy to the material. This is directly related to both the exposed surface area and thickness of the material. In a 24 hour period it is most significantly the first 5 cm (~2”) layer of a material that matters in heat storage. It has even been asserted that use of heavy-weight concrete with thickness greater than 10 cm (~4”) makes little impact on thermal inertia heat storage behavior in a building [Zhang and Wachenfeldt, 2009].

THERMAL MASS USES: PAST, PRESENT, AND FUTURE

Thermal inertia is not in fact new, though it is touted now as a popular new energy savings strategy to be found in modern “green” designs. It was popular in the 1960’s and 70’s and even when not advertised as such has tended to be used all through history in areas where it provides practical benefits simply due to the natural evolution of regional construction as people adapted their structures to local conditions. This “innovation” in design today actually signifies more of a return to the traditional than a discovery of something novel. As is common knowledge, caves were one of the earliest of human shelters. They provided protection from the wild animals and were a place of safety and gathering. Caves also served as protection from the elements and provided some degree of thermal comfort. This is due to the fact that the Earth, in which caves lie, could be considered the largest of thermal mass elements. As mentioned earlier, walls are generally too thin to have enough mass to delay the release of the stored heat energy for more than 24 hours. Just as the thermal mass in a wall can help to maintain room temperatures at the average of the daily external temperature, the Earth has sufficient mass and can maintain a moderate temperature though all the seasons. These early dwelling places protected people from fluxes in temperature and most likely served as inspiration for later man-built structures such as the heavy limestone and mud-brick tombs and palaces constructed in Egypt and the Anasazi and Pueblo communities and houses in what would become the Southwestern United States [Thomas et al., 2004; Chiras, 2002]. What can be learned from these ancient peoples is that though this thermal inertia effect occurs naturally due to the physics of heat flow and material properties, the effect can be greatly enhanced when a designer has the foresight and conscious thought to utilize it properly.

Today thermal mass can be seen in buildings in a variety of ways. It can be the use of concrete or stones in the foundation or walls (even just particular walls as mentioned before). Earth-ships have become fairly common today. They have walls made of old vehicle tires stacked and packed with earth and rocks where the thick-packed soil acts to some extent as thermal mass to regulate internal building temperatures. Also sometimes employed are huge water tanks (above or below ground) that work because of water's relatively high specific heat capacity. These water tanks, however, seem to have shorter delay times as they lose the heat fairly quickly. Also pipe systems can be used that go deep into the earth to utilize the earth's mass as storage (geothermal pumps). These systems pass fluid through the pipes to cool or warm it relative to the air temperature at the surface and this fluid is then circulated through the structure to stabilize the building's internal temperature. Sometimes the pipes are not filled with fluid but are left open to make a path with the Earth to use it as a thermal sink or source. Houses dug into the Earth have also found their popular niche today. Leading the way to the future of thermal mass, however, are phase change materials such as paraffins.

Thermal mass has had many applications to improve the thermal comfort in structures throughout history but it also has common use today. Earth sheltered houses are detailed both by Anselm, 2008, and by Chiras, 2002. These types of structures are successful at regulating indoor thermal comfort because the Earth's temperature is much more stable year-round in a location (around the average of the air's annual dry-bulb temperature) than the outdoor air temperature is. In the summer the ground is cooler than the air, and in the winter it is relatively warmer. The ground temperature, and thus the benefit of course, also depend on the depth into the soil. The temperature tends to be less effected by the outdoor dry-bulb temperature as depth underground increases. An equation is presented by Labs, 1979, to estimate the ground temperature at a certain day of the year and depth into ground based on the average ground temperature and the soil's thermal diffusivity. This is useful to analyze the potential benefits or detriments of this type of Earth structure in a certain locale. The building is passively cooled through the summer and passively warmed in the wintertime by the Earth itself, which forms some if not all the walls of the structure, because heat travels from warmer to cooler regions. It is emphasized that increased heating and cooling benefits, as well as better indoor conditions, are achieved as the percentage of the façade in contact with the ground increases [Anselm, 2008]. For this reason, Enveloped buildings (those with all the external walls in contact with the ground) are found to perform better passively than Bermed buildings (those with only some of the external walls in contact with the ground). The energy efficiency of the space conditioning is improved with greater building surface contact with the ground. However, a potential downside is noted by Anselm, 2008, that "there are some heating and cooling losses through the soil" as the Earth is absorbing the energy used to further condition the space. This loss could perhaps be negated with the use of a small amount of insulation like Chiras, 2002, advises about slab insulation. Moisture in the soil (such as after a rain) can also reduce the benefits of the thermal mass, due to the fact that water has a high specific heat capacity and also high conductivity as mentioned earlier. The thermal conductivity of a mass of soil tends towards that of the main material in the soil—be it water, ice or solid granules [Freitag and McFadden, 1997; Farouki, 1981]. Thus, these properties of the soil can further the losses acknowledged by Anselm, 2008.

Rammed earth buildings also use the properties of the ground but in a slightly more sophisticated and controlled way. For a rammed earth wall, basically a wall frame a few feet wide is filled with earth that is pounded down (usually manually) before another layer of earth is added and once the wall is filled it is sealed. This seems simple enough but usually must involve heavy machines to move the dirt. With rammed earth theoretically the moisture and contents of the soil can be monitored to achieve optimal thermal results. In Taylor and Luther, 2004, rammed earth is used in an office building with night ventilation and it is described as low resistance, high mass material. The authors show that despite the relative conductivity of the material, its large thermal mass slows and reduces heat transfer overall into the room and even produces a cooling effect during the day in the southern wall. This of course, is beneficial in hot environments and reinforces the fact that the performance of a material cannot be based on the conductivity alone when considering thermal mass but also the dynamic properties of the material.

A Trombe wall, as described in Chiras, 2002, is a singular massive wall in a building that perhaps has a pane of glass on the exterior (like a double facade) to trap and absorb sunlight for heating purposes. It is understood that these walls function ideally when facing south absorbing the early morning sun in winter to assist in heating. The majority of the heat gain in a building (desirable or not) is from the sun thus, as mentioned previously, the orientation of the wall does matter in thermal storage as thermal inertia is affected by the path of the sun though the day and the year. Therefore, a Trombe wall, like any other type of thermal inertia material must be purposefully placed with the function of heating or cooling in mind. These walls are most commonly utilized in heating environments and positioned to face south to maximize the exposure to the sun throughout the day.

Passive thermal storage systems are those thermal inertia systems described thus far in this paper, where either completely passively, or through the use of pre-cooling, the building stores and releases heat as the day progresses. An active thermal system, on the other hand involves piping, chilled fluid through the thermal mass or even through phase change materials. “Active technologies require additional devices to collect, distribute, and control the systems that provide thermal energy” [Russell and Surendran, 2001]. This type of storage can save money by permitting the use of off-peak electrical charges for cooling air or freezing liquid media and also allows utilization of the increased COP in the cooler nighttime hours. Over the night these systems thoroughly release the heat that had been stored in the thermal mass during the previous day allowing successful capture of the next day’s heat energy. Thermal mass is seen to be quite successful when both passive and active systems are employed for reducing the overall energy costs [Henze, 2005]. Russell and Surendran, 2001, note that it is important with this control strategy not to “under cool” the thermal mass which could result in discomfort for the first of the next day’s occupants and could lead to condensation, though they did not witness any moisture problems in the study. They find that the use of three active cores (cooling pipes) in the thermal mass (most successful closest to the room side) could increase the cooling potential by 335% more than the effects of night cooling.

Russell and Surendran, 2001, propose that piping a cooling fluid through the building mass can further the potential of the thermal mass to absorb heat energy and to stabilize the internal temperature in the room. This idea is similar to that of using air to purge the heat from the building mass. However, they caution against the possibility of overly cooling the mass since this can defeat thermal comfort and potentially allow for condensation on internal wall surfaces. The correlation between the temperature in the pipes and the internal surface temperature appears to be precisely linear and this can facilitate the correct implementation of this strategy to avoid over-cooling (and consequently moisture problems). In the study they find that this method can lead to a cooling potential increase much greater than that provided by effective night ventilation given by Arnold, 1999, with little risk of condensation. This could make thermal mass more useful in areas that have less extreme diurnal temperature swings. Thermal mass has been demonstrated to have a beneficial effect on the cooling and heating loads of buildings and these effects can be enhanced greatly by controlling the design and systems to make the most of thermal inertial strategies.

There are possibilities of small applications of thermal inertia such as utilizing the thermal mass of gravel. Al-Turki et al., 1997, has done some analysis of the use of gravel on roofs to improve the energy efficiency of a building. The gravel traps air between the individual pieces and this air acts as additional insulation to the roof, resulting in the emittance of less heat back into the atmosphere during the night. The gravel exhibits thermal mass behavior due to the mass of the individual pieces and it is reported to shift the heat gain and heat release in the roof slab by nearly 3 hours in the morning and at night. The authors of the study show that increasing the gravel grain size marginally increases the heat transfer to the surface of the slab, but increasing the amount (mass) of gravel decreases the heat transfer by a much greater extent. Hasnain, 1998, refers to a modification of this concept as "packed beds storage" where warm air is directed into the bed to deposit heat where it is stored until needed and collected by passing cooler ambient air over the rocks. He mentions that ~36kJ/kg (10^5 kJ/m^3) can be stored in rocks and concrete resulting in a temperature change of 50 degrees Celsius. Any fluid can be used for this technique, not just air. The same concept of the packed rock beds can be applied to a "fluidized bed," which allows faster heat transfer between the media [Hasnain, 1998].

Other uses of thermal mass are floor warming and cooling by passing heated or cooled air through the massive floor slab. Similarly, hollow core ventilation is used where conditioned air is released though the floor slab to integrate it with the thermal mass [Hasnain, 1998]. Hasnain, 1998, also mentions the possibility for high temperature thermal storage in metals or salts.

Liquid media such as water, salt water, petroleum based oil, and molten salts in tanks or pools could be used to store thermal energy for later release, yet each of these poses potential problems regarding the storage of the fluid itself. Of the water types, different energy storage results can be achieved depending on the amount of convection or the stratification of the water. The molten salts and oils generally have much higher specific heat capacities than water, yet they pose even greater problems in containment [Hasnain, 1998].

While looking to traditional passive heating and cooling strategies is important, so too is the development of new technologies that can be applied with traditional techniques to optimize the energy efficiency. Such components of thermal mass being researched are phase change materials and active heat sink materials within the building envelope, as described previously. Many phase change materials (PCM) are in research presently for use in thermal inertia strategies. They can store and release much greater amounts of energy (both sensible and latent) by going from one phase to another. For instance, solid water absorbs energy to become liquid water (latent heat of melting) and liquid water in turn releases that same amount of energy (now latent heat of fusion) to become ice. This can be controlled and harnessed to enhance the thermal storage in building materials to store both sensible heat energy and latent heat energy of phase change. There are many requirements for the behavior of the material that restrict the selection of PCMs potentially available for the use. For instance, such PCM materials must change phase within the temperature range of the system to be of benefit. The types of PCM available are inorganic compounds (salt hydrates, salts, eutectics, metals, and alloys); organic materials (paraffins, non-paraffins (fatty-acids), and poly alcohols). The material must be arranged such that there is a large surface area exposed to the heat transfer mechanism and they must be stored in a way to account for both liquid and solid phase properties. Many solid-phase PCMs have insulating properties so a method of heat transfer should also be considered in designing a system that retrieves latent heat, such as fins or metal pellets. Characteristics to look for in a good phase change material are as follows: high heat of fusion, little super-cooling, low vapor pressure, chemical non-reactivity (stability), self-nucleating, non-segregating in phase change, low cost, high conductivity, and small volume change. In one practical application it has been shown that gypsum wall board can be inserted with phase change materials to add the latent storage to the sensible storage capacity of a building [Hasnain, 1998].

Also, Nagano et al., 2006, designed a special ventilating apparatus involving the phase change material paraffin wax that had been absorbed into the pores of recycled foamed glass beads. The authors determined the probable amount of stored heat in the night, including the concrete thermal mass and massive floorboards, to be ~2.6MJ/m^2 with the PCM in a layer directly below the porous floorboards. This could be considered a significant amount of energy saved due to the proper implementation of thermal mass and PCM technology. There is still much research to be done to optimize the utilization of PCMs in thermal mass but there is also much potential.

CLIMATE CONSIDERATIONS AND TRADITIONAL DESIGN

There are many different ways to employ thermal mass in buildings today but proper implementation of thermal mass depends on the climate under consideration. To successfully design with thermal mass, or any sustainable design technique, it is vital to consider the location of the building being designed. In many cases this can involve looking into ancient modes of design specific for the region. Hundreds of years of experience in a certain climate tend to produce functional building designs that work for the optimal degree of thermal comfort (even before mechanical conditioning was developed). This doesn't necessarily mean that the historic ways of design would produce comfort levels approved by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), yet it may be the best possible design for a given climate with a given technological level.

Yilmaz, 2007, discusses the differences in traditional architecture found in the hot-dry region of Turkey (Mardin) and the temperate-humid climate (Istanbul). Mardin contains traditional buildings that have envelopes with high mass materials with large heat capacities (masonry is common) and with very low wall transparency ratios. In Istanbul it is noted that the massive envelope is less a concern but thermal insulation of some form is commonly used along with large south facing windows and a wind-protected northern façade. Also the arrangement of traditional buildings in Istanbul is such that the southern radiation on any building is not blocked by another since the southern exposure is so important for heating in the cold winter. These traditional design strategies represent what is being learned presently in sustainable architecture as important principles, yet in many places such as Turkey, the traditional has been abandoned for what is modern and what has met success in other areas. This is commonly the case even if the design doesn't fulfill its potential in that climate region. Slowly, with the present green movement, it is becoming understood that a specific building must be designed for a specific climate. Engineers are beginning to look back toward what has worked hundreds of years ago and are finding that the same is applicable today for reducing energy demands for heating and cooling loads in those regions. Similarly, builders in the Negev desert in Israel commonly uses massive wall materials in local design, such as standard hollow concrete block (HCB) and autoclaved aerated concrete block (AAC) [Huberman and Pearlmutter, 2008]. Another example is found in Fathy, 1973, where he notes how housing in rural Egypt utilizes thermal mass effects with mud-bricks effectively today, much as it has for centuries.

DOES THERMAL INERTIA SAVE ENERGY?

Thermal mass has been defined and some functions and applications specified, but can it truly be classified as an energy efficient technique? Does thermal mass save actual energy, or just the cost of electricity due to the lag effect allowing for the utilization of less costly off-peak electricity? Varying and sometimes conflicting answers to these questions are found throughout the literature.

Henze et al., 2007, definitely finds a correlation between energy cost reduction and thermal mass used with a pre-cooling strategy. For the masses tested however, he reports that the best cost savings were associated with the lighter mass level (the half—2” and baseline—4” thicknesses) rather than for the largest masses (2 and 4 times the baseline thickness—8” and 16”). He reached the point where increasing the mass no longer increased the total cooling benefits due to less savings in operating costs though he shows that the total noontime cooling load does continue to decrease as thermal mass thickness increases.

In an earlier paper Henze, 2005, concludes that the energy saving case in his paper is not successful for saving energy or costs, yet he proposes the use of both active and passive thermal storage together could achieve great savings in cost over conventional building operation. The negative results could be due to the fact that his “energy saving” case did not incorporate pre-cooling of any kind and no thermal inertia effect was noted for that case. Zhu et al., 2009, also find less than satisfactory results in the hot-dry climate of Las Vegas, Nevada. They do find some negligible energy heating benefits in the winter but determine that the effect of thermal inertia is not cost effective in that region as the walls actually seem to have a warming effect in the summer as well. The thermal mass is assumed to absorb too great an amount of heat energy during the day that it’s not able to purge it all through the night. This leads to a build-up of energy and ineffective cooling. They find that the system is the most successful during the intermediate times of the year. These results stand in stark contrast with others representative of thermal inertia behavior in hot-dry climates and perhaps this is due to the walls in this study being “too thick” or massive, as seen by Henze et al., 2007, (in Phoenix) where the most massive walls in that study (8” and 16” concrete) do not save total electricity.

The wall in the Zhu study has about 6 inches total concrete but there is within it 2 inches of internal insulation. The lack of effectiveness of the thermal inertia in the Zhu study could also be related to the positioning of the insulation. External insulation works well with thermal mass and interior (room-side) insulation hampers the effects of thermal mass. It is possible that this is also the case when the insulation is sandwiched within the wall.

Conversely, Aste et al., 2009, reveals that thermal mass design can save about 6% in heating and 21% in cooling energy based on simulation. Burch et al., 1984, reports a decrease of 40% in the combined heating and cooling loads of a building when thermal mass is coupled with night-temperature set-back savings.

Also important for consideration is the embodied energy of a building and its constituent materials. It was once considered to be a small portion compared to the overall energy consumption of a building but recently it has been shown to actually be significant. Huberman and Pearlmutter, 2008, cite that the embodied energy could actually be in the range of 20% of the total life energy of the building. Of course the percentage of embodied energy in a building depends on its lifespan and annual operational energy use, but other studies have shown the embodied energy of buildings to fall within 10-60% of the total-life energy [Langston and Ding, 2001; Thormark, 2002; Milne and Reardon, 2004]. As people have moved away from the traditional designs and local materials of a region, builders have become more reliant on bringing in material from farther away. This transport in itself leads to higher embodied energy but also many newer materials being manufactured are produced in ways that have high energy costs. Certain materials can be very useful in reducing the operational energy cost but are actually very high in embodied energy from production. Insulation is one such material [Huberman and Pearlmutter, 2008]. This embodied energy can be reduced by using recycled or reused materials or by using sustainable source energy in the production process. It can also be reduced simply by being educated about the production energy of certain standard materials and utilizing that energy in the design process. In the study by Huberman and Pearlmutter, 2008, for the Negev desert it was found that the reinforced concrete building used the most cumulative energy through its lifetime, 2/3^{rds} of which is due to embodied energy in the concrete production process. The most successful building in the study is built with stabilized soil block (which has a higher specific heat capacity than the more common fly-ash block). This material can be made locally in many areas but not the area where the study took place. The total energy here is reduced from that of the reinforced concrete by 20% and the operational energy for this material is only about 15% over that of its operational energy use. The stabilized soil block was the third best material for reducing embodied energy (the first was the fly-ash block) and the second best for operational energy use (the first was the reinforced concrete). The reinforced concrete had the worst embodied energy content. It should be emphasized that the reinforced concrete used over 17% less energy in operation over the worst operational case (the autoclaved aerated concrete block) yet it was 33% worse than the best embodied energy case (the fly-ash block) resulting in a cumulative energy usage about 20% worse than the best case. All the materials in this study lead to higher embodied energy than operational energy usage but great differences in the overall building energy usage are revealed. In this study are certain embodied energy values for these materials in the Negev desert which included material production, transportation, and building construction. Some values are as follows: concrete—2,852 MJ/m^3, reinforced concrete—6,230 MJ/m^3, hollow concrete block—1,216 MJ/m^3, fly-ash block (soil)—179 MJ/m^3, stone—1,890 MJ/m^3, and expanded polystyrene— 2,710 MJ/m^3.

Hacker et al., 2008, calculated that compared with the light-weight case, his more massive case results in an embodied energy of 15% yet saved 17% in operational energy expenditures, resulting in an early “payback” of the initial energy. They find in their analysis that a medium-weight building could achieve payback in 11 years and the heavier-weight cases between 21 and 25 years. This is considered relatively short given an expected lifespan of the building of several decades. The heavier-weight buildings are the same as the light-weight but include concrete in the external and internal walls and the ceilings and floors.

Overall, thermal mass does seem to save both operational energy and electricity cost by reducing the number of hours cooling is required (or the amount of heating) in most cases (especially with effective night-cooling strategies). It also is effectual at not only reducing the peak load but shifting it so that there are additional benefits such as allowing the HVAC system to perform under an increased COP since the peak indoor loads no longer coincide with the peak outdoor loads. However, the embodied energy consumption depends entirely on the massive material chosen for use in the structure and can vary by region, building type, and expected lifespan. This also depends on what any certain material is being compared against.

THERMAL MASS IN HOT-HUMID ENVIRONMENTS

Overall the literature either does not mention or is not found to be favorable towards thermal mass use in a hot-humid environment. It is postulated that this is due to the humidity in a region producing more cloud cover than in a hot-dry area. This cloud cover could then act as insulation keeping the warmth of the day closer to the earth rather than allowing it to be transmitted back into the atmosphere. This could possibly lower the daily temperature swings which are so vital to successful thermal inertia applications. This conjecture is trying to correlate why latent energy (humidity) could affect the sensible energy storage of thermal mass. Based on eQUEST weather data for the typical meteorological year, daily temperature differences are equal or larger in Austin than those in Phoenix for about 25% of the year and more frequently in the winter season. This is a pretty large percentage but still could be the reason behind the projected difference in thermal mass performance.

Yilmaz, 2006, mentions that it is not necessary to use thermal mass in buildings in hot-humid regions (compared with hot-dry) but does not mention that if the use of it would have detrimental effects on space conditioning. The solid masonry wall in this experiment is not tested in the humid region and the concrete walls tested do include insulation on the room side which has been shown in other studies to negate thermal inertia benefits. However, in his study it is shown that the solid masonry wall performs better in the hot-dry region and the concrete wall with insulation inside performs better for the hot-humid region. This is compared to a third option, a gas-concrete wall (a type of light-weight concrete) that is insulated on the room side, with the same insulation properties. It can be assumed that the better performance of the concrete wall types in the hot-humid environment is not just due to the additional insulation but also the use of concrete since the lighter-weight gas-concrete and regular concrete walls are identical apart from the different concrete materials specified. The light-weight concrete wall performs better in the summer with less heat gained, but the heavier concrete wall performs much better in the winter with less heat lost resulting in higher annual benefits associated with the heavy-weight wall. It is possible that the interior insulation is negatively affecting the summertime performance of the heavy-weight wall. If the concrete wall structure in the study were used in regions where thermal mass has no impact on operational energy then it would be wasted embodied energy, as massive elements tend to have larger embodied energies. Al-Homoud et al., 2009, discusses the thermal comfort year round in mosques in a hot-humid climate and envelope insulation is indicated as being very important to the thermal comfort (as is air-conditioning usage) yet there is no indication of whether massive elements are beneficial.

Despite this, one paper is found that does perform analysis between thermal mass and light-weight structures in the hot-humid climate of Nairobi, Kenya. This study seems to corroborate all that is known about its beneficial effects in hot-dry climates for hot-humid climates also. Specific to the hot-humid region is mention of the swing in relative humidity within the structure throughout the day from the highest 65-75% in the early morning when temperatures were the coolest, to the lowest from 17-31% in the heat of the afternoon. These tests are done without the benefit of air conditioning [Ogoli, 2003].

Though results from most previous studies either neglect or discourage thermal inertia in hot-humid climates the data seems to indicate potential positive outcomes and energy reductions due to thermal mass use. Thermal mass is simulated on a typical small office building in Austin, TX and the benefits are compared with those from the implementation of the same building in Phoenix, AZ. This study successfully witnesses reduced energy consumption for thermal conditioning when thermal mass is utilized in Austin.

METHODOLOGY

The purpose of this a paper is to compare the effects of thermal mass in buildings in Austin, TX so effort has been expended to produce a baseline design in eQUEST that is representative of the typical commercial building in Austin, TX. However, though typical Austin properties are desired, it doesn't affect the validity of the paper if some properties aren't strictly as common in this area because the comparison with the other climates uses the exact same building models. The end goal of this paper, to witness the benefits or detriments of thermal mass in the hot-humid climate of Austin, TX compared with the known benefits in hot-dry climates like Phoenix, AZ is not deterred by any misconceptions by the author regarding what is considered standard for the region. The building parameters not specified are no different than those indicated by eQUEST for a small office building.

BASELINE MODEL PARAMETERS

In this analysis the utility information is ignored so just peak power use, and not cost, will be investigated. The eQUEST model building faces north to simplify the observation of solar effects on the thermal mass. It has three above grade floors and no below grade floors, each with dimensions 91.3 ft by 91.3 ft. The building is square for ease in observing the impact of thermal mass on specific walls. The above grade floors allow the building to have a bit of a rise but according to the DOE, 2003, buildings greater than 3 stories make up only about 2% of the commercial buildings in the South. Therefore to make this building a standard commercial building in the region three floors are selected. There are no below grade floors since basements are rare in Texas. The building is 25,000 ft^2 because, based on DOE, 2003, data, about 90% of the commercial buildings in the US are 1,001 to 25,000 ft^2 and energy consumption tends to increase with size. For instance, the largest buildings (>200,000 ft^2) are the fewest in number yet contribute to more than 25% of the US commercial building energy use. Thus, the larger size for that common range is selected to be analyzed as a normal US office building that could make substantial use of improved energy efficiency. Floor-to-floor heights are 12 ft and floor-to-ceiling, 9 ft—both standard commercial building dimensions. The roof has no pitch or overhangs in accordance to common small commercial building design in Texas. There are five conditioning zones in the building with a perimeter zone depth of 13.5 ft, so that the area of the perimeter zone is nearly equal to that of the inner zone. The total percent glazing for the floor-to-ceiling wall area is 30% with window dimensions of 6 ft by 6 ft (3 ft sill height and frame width). The frame is identified as aluminum with a thermal break. Window placement is the same on all sides of the building to keep the effect of windows on the analysis constant. The window properties are chosen to reduce the effects of solar gain through the windows to emphasize the effects of the thermal mass. The glass selected is "double reflective, A-L, clear ¼ in, ¼ in air (2400)." In the HVAC system DX coils are used for cooling and heating (heat-pump) with air as the heat pump source. The system is a split system single-zone heat-pump divided by zones. The infiltration for the internal zone is 0.001 CFM/ft^2 and 0.038 CFM/ft^2 for the outer shell. There are no exterior end-uses and the return air system is plenum instead of ducted.

The roof is built-up and the construction is metal frame, 24" o.c., with 6 inch polyurethane (R-36) and a radiant barrier with no batt because roofs in Texas face a lot of sun. This insulation is chosen in order to exceed the DOE recommendation for increasing insulation on the roof over an R-value of 30. Commercial buildings (especially those over a single story) tend to have metal frames rather than wood. The above grade walls are also steel framed (2"x6," 24" o.c.) with concrete finish, 3 inch polyurethane (R-18) insulation, and zero furring insulation. The insulation is decided based on the DOE's recommendation of R-11.7 on exterior of masonry walls [ORNL, 2008].

There's a 4" concrete slab with earth contact and no perimeter insulation for the ground floor. During cooling periods, a less insulated slab appears to be more energy cost saving than a well-insulated slab and the opposite is true for a heating period [Zhu et al., 2009]. Since Austin is primarily a cooling zone, the slab is left uninsulated to make best contact with the thermal mass of the Earth. Regarding the interior space, the ceilings consist of lay-in acoustic tile with R-11 batt insulation which is also used for the interior walls. The interior floors are 4” concrete without a light-weight concrete cap or board insulation. The slab does not penetrate the wall plane. All the floors in the building are unfinished to maximize thermal inertia benefits.

Within the eQUEST program the “E.1 Occupancy Profile (S1) Typical” is selected as the daily occupancy schedule and weekends are considered to be unoccupied but holidays are not. The occupancy is important not only because it is during this time that thermal comfort is vital or because the systems are more in use during occupancy but also due to the loads on the building caused by the people themselves. Each office worker can produce 132 W of internal heat gain into a room (with 54% of that sensible and 46% latent) [Henze, 2005].

THERMAL MASS BUILDING MODELS

The design detailed above is the eQUEST baseline model representing a standard commercial building in Austin, TX (Figure 1). The building layout, the HVAC system, the windows and doors, the internal ceilings and the occupancy all remain constant for the remainder of the analysis. There are six wall systems investigated beyond the baseline: the massive; the 1.5 massive; the ½ massive; massive with no insulation; massive with internal insulation; and massive with major insulation. These situations are meant to investigate the importance that insulation and thermal mass thickness have on the energy efficiency of the building compared with the baseline. Except in the cases where the insulation is explicitly described it is to be considered the same as the baseline. The massive building has 8 inches of concrete in the roof and a layer of gravel on the top of the roof. The walls and ground floor slab are 12 inches of heavy-weight concrete. The internal walls are "massive" and the internal floors are 8 inches concrete. This may seem extreme but this envelope was created to see a significant impact on the power savings and it appeared to be more successful than less-massive cases. The parameters thus far are created in the "wizard" mode of the eQUEST program. The rest of the cases are modified versions of this massive case using the "detailed design" mode or eQUEST from which one cannot return to the simpler model.

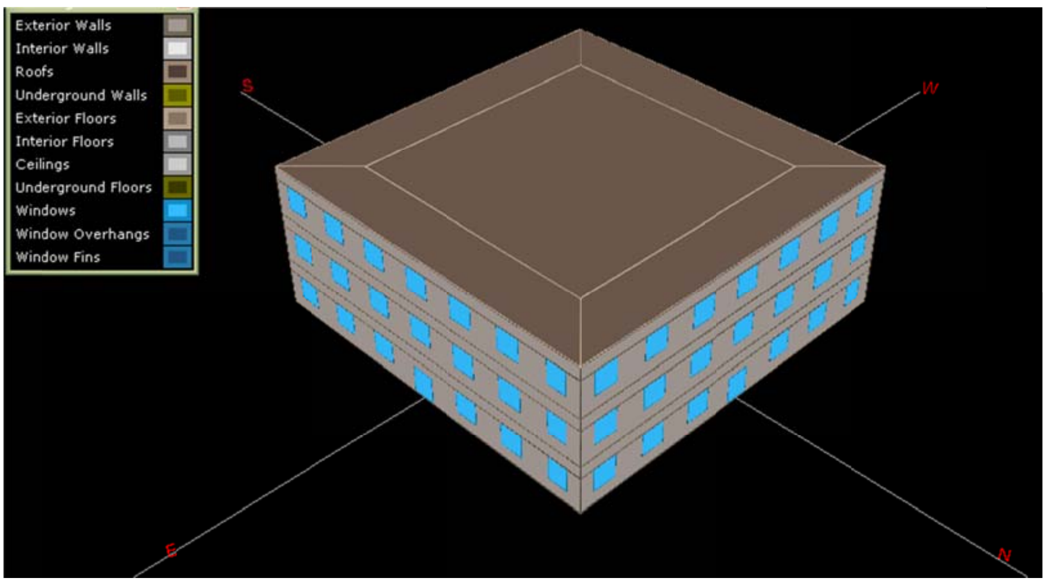

Figure 1: 3D schematic of baseline building model on eQUEST.

The ½ massive case is based on the original massive model and thus remains the same except that the concrete in the exterior walls is 6 inches thick and the roof 4 inches thick. The massive 1.5 case is like the massive model but the exterior wall and the roof concrete both are now 1.5 ft thick. This is the maximum permitted by eQUEST and it still seems to yield some improvement over the massive case, implying that if the walls could be made thicker there could be still greater peak power savings. The next cases are all the same concrete level as the massive building but the insulation level is adjusted to verify the claims about the benefits of exterior insulation in thermal inertia systems. In the "No Insulation" case all the insulation is removed from the massive model resulting in no external board insulation on the roof or external walls and no ceiling insulation inside. Note that the internal walls and the floors in this model are already without insulation. Next, the insulation is replaced but on the room-side of the massive element on the external walls to create the internal insulation case. The insulation chosen in each location is exactly the same as the insulation in the massive model only that it is now on the room-side. Also all the floors now have carpet covering with a rubber pad and the interior floors also have a 1.25 inch light-weight concrete cap and 2 inches of polyurethane (R-12). The final insulation investigation is the major insulation case where the exterior insulation level only is enhanced from the massive model. The changes in this case are that the wall insulation (exterior) has been replaced with 3 inches of polyisocyanurate (R-21) and the roof insulation with 6 inches polyisocyanurate (R-42) and a light-weight concrete cap. Because the HVAC system doesn't use natural gas there is only electric consumption in the building. This electrical power consumption is compared between the models is compared and the massive model is the most successful of these seven envelope cases at reducing the peak power consumptions.

SPECIALIZED GEOMETRIES

Also of interest is whether the geometry of the building with specialized walls has a significant impact on the power consumption of the building. Eleven different geometries are evaluated to determine the effectiveness of specialized walls to optimize peak power savings. In these cases light-weight refers to using the baseline wall or roof design, medium-weight refers to the massive case components and heavy-weight to the 1.5 massive envelope systems. There is also a light-weight wall with lots of insulation where the external insulation thickness is doubled from 3" to 6" polyurethane and in the roof R-30 batt is also added. When the internal walls are heavy they are 12 inch concrete. The geometries are based on those proposed by Barmpas et al., 2009, to be ideal for dampening and delaying the peak load. The literature recommends making the east wall and roof either extremely massive or extremely insulative (with little mass) to avoid the release of heat into the building during the late afternoon. It also suggests medium-weight walls for the west and south and light-weight walls for the north. For geometry 1 the east wall and the roof are heavy; the west, south, and internal walls are medium-weight; and the north is light. These are the same for each floor of the buildings. Geometry 2 is the same but with the internal walls all light-weight to observe the impact of internal thermal mass on the building. Geometry 3 is like the second but the internal southern wall is heavy-weight on all floors to simulate a type of Trombe wall. In the geometry 4 all the internal walls are heavy and in 5 all the interior and exterior wall systems are heavy (this case would be like the 1.5 massive case with heavy internal walls too). Geometries 6-9 repeat the same pattern except that for these the eastern walls and the roof are light-weight construction with high insulation levels. Also, for the sake of comparison, a "water" Trombe wall is simulated to replace the internal southern walls in geometries 10 and 11 by modifying the physical attributes of the concrete in geometries 8 and 3 respectively to act like water. The density is changed to 62.13 lb/ft^3, the conductivity to 0.34 btu/hr-ft-°F and the specific heat to 0.998 btu/lb-°F and these values can be found in Table 1.

ADDITIONAL MASSIVE MATERIALS

Once the most optimal building geometry is selected the materials are adjusted and the concrete in the walls is replaced with the properties of "adobe block," "granite stone," and "rammed earth." These are compared with the heavy-weight (140 lbs) concrete used in geometry 5 and these properties are listed below in Table 1. The thicknesses remain constant between the cases for this portion of the analysis. These materials are not feasible for use in the construction of a three story office building but it is their properties that are investigated, not the materials per-say. There are many types of concrete and it is possible to select a type that embodies similar properties to one of these materials that could be used in a three-story construction. The materials are selected solely as a means to compare different material properties. These material are tested in geometry 5 initially only in the external walls, then these modified external walls without insulation are tested and finally the "all" case is where the all the concrete in the external and internal walls is replaced. The roof composition remains constant as concrete through this process.

Table 1: Dynamic thermal properties of select materials.

References	Material	Typical Thickness (ft)	Conductivity (btu/hr-ft-°F)	Density (lb/ft^3)	Specific Heat (btu/ lb-°F)
Szokolay, 2008	Adobe Block	1.5	0.722	127.920	0.239
Szokolay, 2008	Granite Stone	1.5	1.329	162.240	0.196
Yan et al., 2005	Rammed Earth	1.5	0.416	113.818	0.215
	Water	1.0	0.335	62.132	0.998
eQUEST (version 3.64)	Heavy-weight Concrete (140 lbs)	1.5	0.758	140.00	0.200

These cases now are used to optimize the geometry and the properties of the materials from the baseline design in Austin, TX. The granite stone "all" case of geometry 5 is found to be the most successful of all the cases explored in this study. Next certain external parameters are varied, modifying some of the original parameters that have been held constant in order to view this impact on the thermal mass building in Austin. The effects on thermal inertia of shading, window covers, and day-lighting are investigated. It has been stated that pre-cooling thermal mass buildings reduces energy cost [Henze et al., 2007] and also this effect of pre-cooling is investigated as to whether it also reduces peak power usage.

EXTERNAL PARAMETERS

To implement exterior window shading 1.5 ft fins and overhangs are added to all the windows in the model. Dark horizontal blinds are selected as a window cover where 20% of them are closed during occupied times and 80% closed during unoccupied times. Day-lighting is selected to be day-lit from side lighting and to use the simplified eQUEST method with one photosensor per zone, where 100% of the lights are controlled and the design light level is set at 50. The photosensors are located 2.5 ft above the floor at 50% of the zone depth. The lighting level is controlled by dimming it to 30% artificial light. The night ventilation cycles fans at night allowing the minimum outdoor air at night while utilizing an economizer. No change is made to the economizer from earlier models. The fans are set to be on intermittently via control zones but to operate 24 hours a day. The effect of day-lighting and of the overhangs and fins are both evaluated coupled with the blinds, and the blinds are also evaluated individually, as is the night ventilation. Finally all these parameters are utilized together to produce the most energy efficient building possible for Austin climate and this situation is called “all the extras.” These extra parameters incorporated with the massive model and with the baseline model so there can be no question as to the usefulness of the thermal mass on energy savings. Once the thermal inertia benefits in Austin are established, certain models are tested (with no change at all) in the Phoenix, AZ climate. These are the baseline, the massive, the 1.5 massive, the ½ massive, the internal insulation, geometry 5, and each of the alternative materials (both in the external walls alone and in the “all walls” cases). The electrical power consumption of each of the results is analyzed—specifically the heating and cooling loads, and the pumps and fans. Peak shifting is also discussed so that both results of thermal inertia, the dampening and load shifting of the electrical power use, can be addressed.

RESULTS AND DISCUSSION

Overall the results indicate that the more massive the wall (thicker), the less electricity was consumed over the year (Figure 2). In most cases the thicker walls lead to decreased heating and cooling loads but larger pump and auxiliary loads. There is a significant reduction in the total energy consumption in Austin, TX with the use of thermal mass from the baseline case (2,474,300 kWh) to the optimal case with the extra parameters (2,036,700 kWh) resulting in a savings of 50 kW in a year (437,600 kWh— 17.7% reduction) but there's only around 5 kW (47,500 kWh—2.3%) saved over a year from the baseline case with all the extra parameters (2,084,200 kWh). This results in about a 20% reduction in cooling and an 83% reduction in heating from the baseline case. About 8 kW (69,200 kWh—2.8%) is saved in the optimal case when neither case has the additional parameters included (2,474,300 and 2,405,100 kWh, respectively). The amount of mass creates negligible differences between the thermal mass models, but thicker mass is shown to reduce the consumption by some amount and, as previously mentioned, eQUEST reached its wall thickness limit (1.5 ft external, 1 ft internal) before the thickness stopped increasing the energy savings. It is unknown how much thicker mass would affect this model but it is supposed that this is irrelevant since walls in a commercial building tend not to exceed those eQUEST limits.

COMPARISON OF INITIAL THERMAL MASS MODELS

Increasing the wall thickness from 1 ft to 1.5 ft (massive and 1.5 massive models) lowers heating and cooling loads resulting in a larger difference between the cooling loads in the two cases in the warm season. However, this is a very small difference relatively (less than 1 kW). Decreasing the wall concrete thicknesses (and roof) by half reduces the pump loads in the spring but is worse in all other accounts.

In the massive design the insulation is varied and these results can be seen in Figure 2. It is found that doubling the insulation level negligibly increases the building electrical power consumption. This makes sense because the increased insulation reduces the envelope's link with the internal environment and reduces the benefits of the thermal mass. Otherwise adjusting the insulation levels and positions leads to a much worse power consumption performance compared to the baseline when the thermal mass models incorporate poor insulation design. Removing the external insulation entirely has a significantly negative impact on the electrical power consumption for the whole year but the effect is lessened in the spring and fall. The consumption increases about 5 kW in the months of July and December in the model from the baseline. There is less of a negative effect in the spring and fall because during those times of year the outdoor temperatures are more favorable. Placing the insulation on the internal side of the exterior walls has the same repercussions but to a lesser extent because again the massive element is separated from the area it's meant to condition. In the case with no insulation the building envelope is too related to the external climate since there is no insulation to dampen its affects before reaching the massive wall. When there is no insulation the peak power consumption increases 2 kW in July and 3 kW in December from the baseline model. Again, in the spring and fall this close relationship is not as detrimental because the outdoor weather is more pleasant. Also when there is no insulation, the building is required to heat during more months of the year to maintain indoor thermal comfort. Insulation on the exterior side helps to maintain the heat energy within the system of the building envelope and interior room. This situation with no insulation however does reduce the peak power load for the pumps and auxiliary systems.

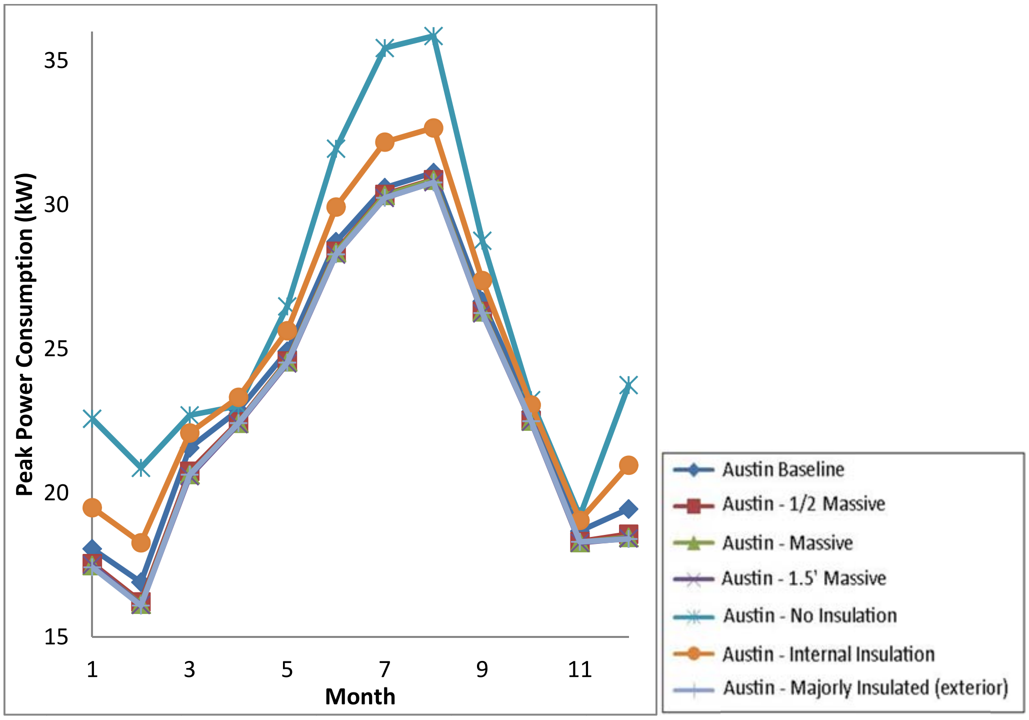

Figure 2: Comparison power consumption due to external walls with concrete thicknesses varied from 6" (half) to 18" (1.5) and from no insulation to high R-value insulation in varied positions. This shows how thermal mass can be of benefit in Austin in different thicknesses with different insulation placements.

COMPARISON OF SPECIALIZED GEOMETRIES

Following the general consensus of the scientific literature the eleven geometries mentioned earlier are developed and compared. The results from these cases are all very close but the first 5 cases seem to do incrementally better (with the highly massive eastern walls and roof). The fifth case marginally consumes the least amount of electrical power out of all of them and it is determined to be the best case in the study based on the way it responds to heating and cooling loads (compared with the massive and the 1.5 massive that had similar annual consumption levels).

The "Trombe" wall geometries are not successful and perform slightly worse in the winter than the other geometries, using more electrical power for both heating and cooling, which is strange given that their main use is in colder regions. It is possible that the building with the Trombe wall was experiencing some kind of overheating in the wintertime based on these results. Overall for the different geometries the differences between the wall constructions were negligible. The aim of this paper is to see whether it is feasible to use thermal mass in Austin to reduce energy consumption, thus the case that consumed the least overall energy (however negligible) is chosen—geometry 5. The case with the smallest thickness of concrete (½ Massive) could have just as easily been selected and probably would achieve similar end results because the difference in energy consumed between the building geometries is so small.

It is also surprising that the specialized wall geometries aren't as effective as just increasing the overall mass of the building by increasing the thicknesses of the internal and external walls and roof. This raises the question again about not reaching the maximum wall thickness that would no longer present any benefit, for once that is found then perhaps the subtleties of specialized walls may have a larger impact.

ALTERNATIVE MATERIALS AND OPTIMIZED THERMAL MASS MODEL

When the concrete model of geometry 5 is compared with the same model with adobe, rammed earth, and granite the difference is small but the granite seems to yield the best results. The least energy consuming case overall in Austin is the situation utilizing geometry 5 where all the concrete in the internal and external walls is replaced with granite properties. This model will now be referred to as the optimized Austin thermal mass design, though the three material properties produced very similar results as seen below (Figure 3). The optimized case performs significantly better than the baseline in the winter and with the additional systems it saves about 5 kW of electrical energy compared with the Austin baseline and 8 kW compared with the baseline in Phoenix (without the extra parameter) in the summertime. Note that the baseline for Phoenix is much worse than Austin in the summer but is somewhat better in the winter.

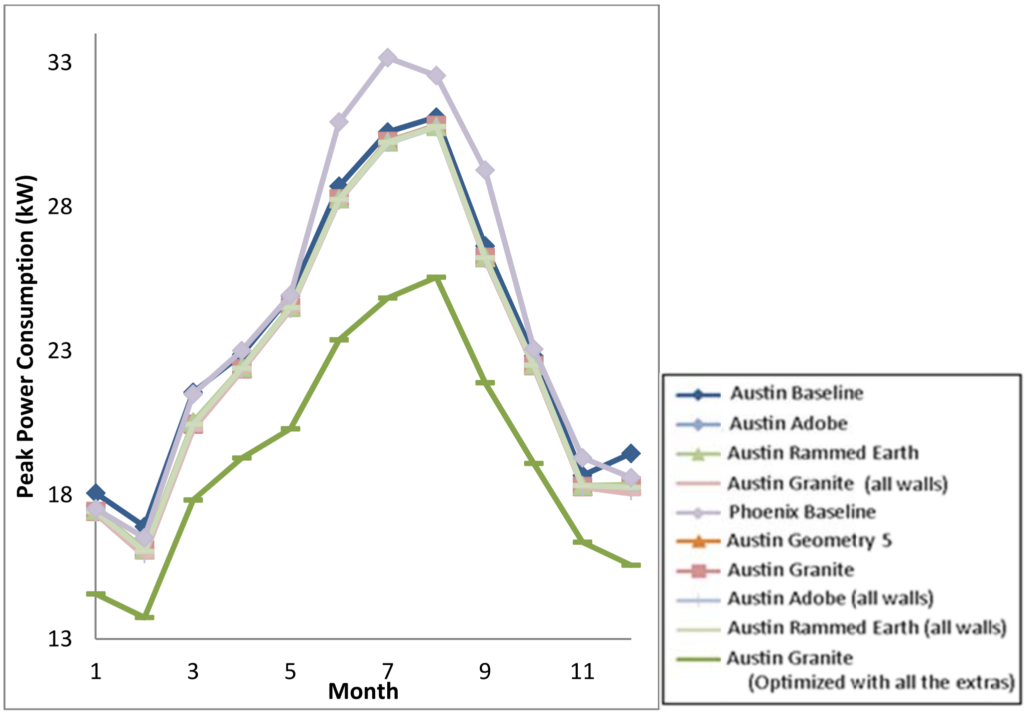

Figure 3: Comparison of the best models to find the optimum thermal mass situation for Austin, TX—compares baseline model with the four different materials. Geometry 5 is heavy-weight concrete and the rest are labeled. "All walls" refers to the external and internal walls having the properties of the specified materials but not the roof or floors (the not-all case just has those properties in the external wall.

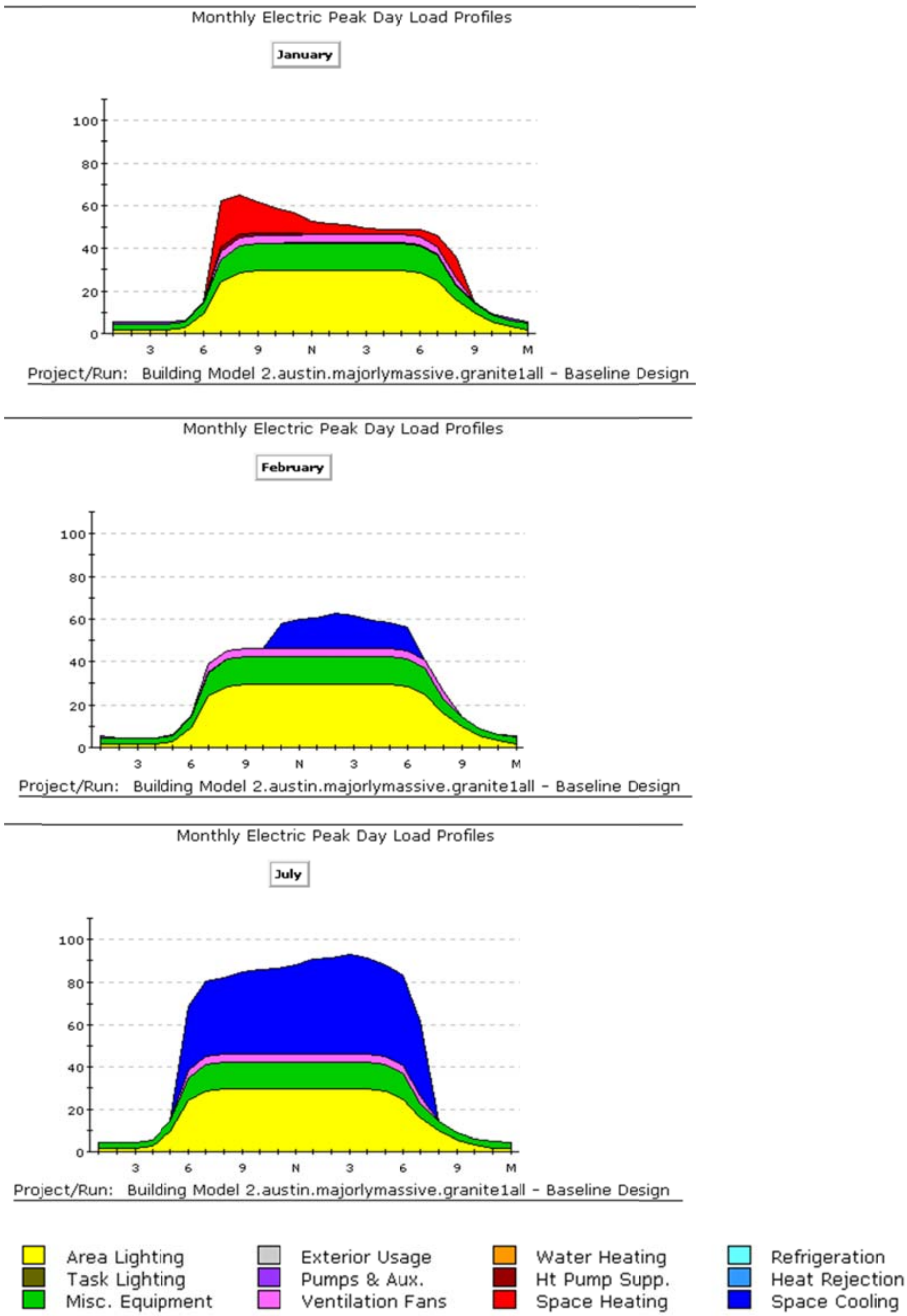

Figure 4: The behavior of the optimal thermal mass model in Austin demonstrated by hourly electrical power loads for an averaged day in the months January, February and July.

In the case of the best model in Austin, the granite internal and external, there is actually some heating load evident in January (Figure 4) that is relieved when the building has night ventilation and day-lighting (Figure 11). In this case for January it is probably the day-lighting that makes the most difference to cancel that heating load. The tendency for load shifting can be seen both in February and in July by the “weight” of the cooling load further to the right on the graphs showing how the building requires cooling later in the day rather than at its peak temperature around noontime.

EFFECTS OF ADDITIONAL PARAMETERS

The effects of certain external variables on the thermal mass and on the baseline model are explored (Figure 5). The parameters investigated are the effects of shading, window covers, day-lighting, and night ventilation with the latter two parameters found to have a large impact on peak power savings. Day-lighting can be seen to reduce overall power consumption by about 25 kW and night ventilation by about 30 kW over a year but these do not include operational costs, just power used. There is a reduction in power consumed when the baseline case employs the extra parameters, but a standard commercial building in Austin would not utilize this and the impact of the external parameters is increased in the massive building model. The largest impact can be seen to be on the cooling loads in the graph in Figure 7, probably because Austin is a cooling dominated climate. The combination of all the extra parameters together leads to the largest peak power saving (Figure 8).

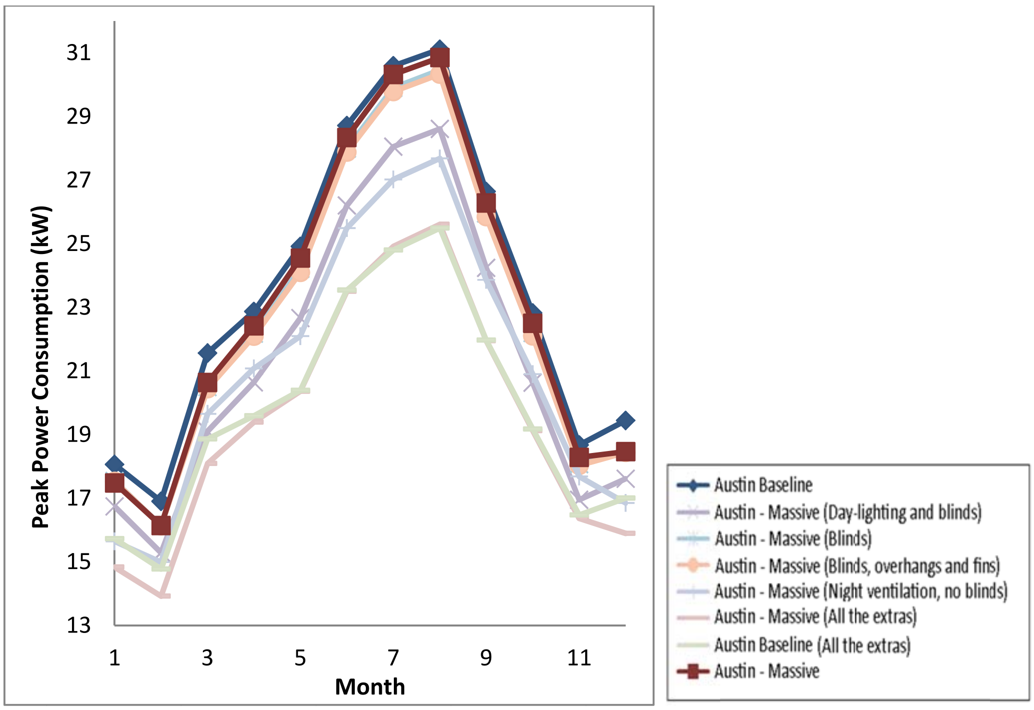

Figure 5: Annual comparison electrical power consumed and how it varies based on the additional external parameters utilized to enhance the effects of thermal mass: night ventilation, day-lighting, shading, and window covers and all of them together.

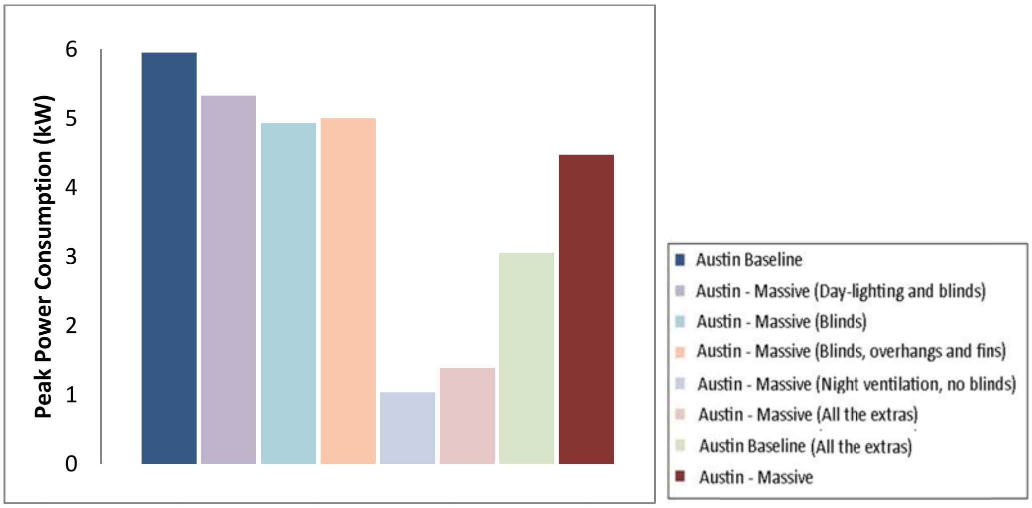

Figure 6: Comparison of the heating electrical power loads of the cases with additional external procedures utilized to enhance the effects of thermal mass.

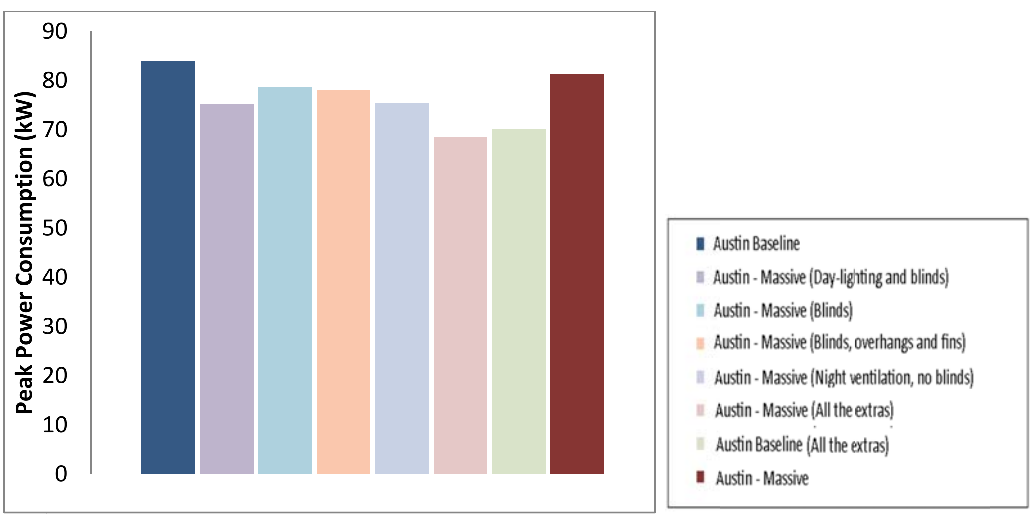

Figure 7: Comparison of the cooling electrical power loads of the cases with additional external procedures utilized to enhance the effects of thermal mass.

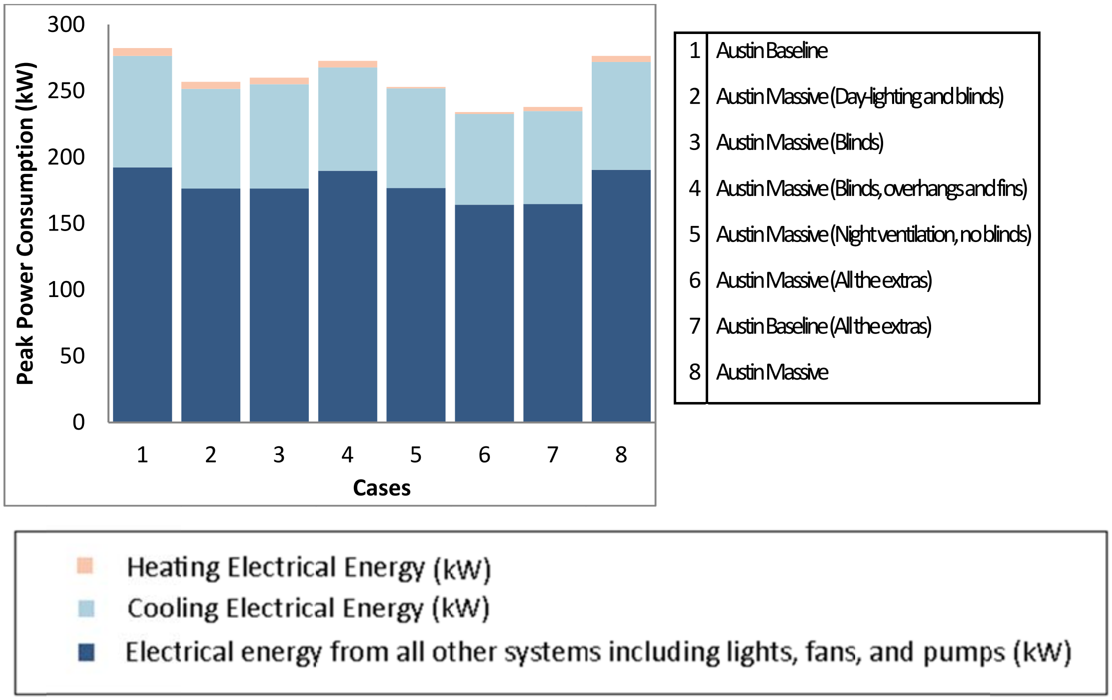

Figure 8: Comparison of the overall electrical power loads of the cases with additional external procedures utilized to enhance the effects of thermal mass broken down into the heating, cooling, and systems components.

The night ventilation makes a big improvement in the summer and winter but isn't quite as successful in the spring and fall. The fins and the blinds have the least impact on the electrical power consumption but they have more of an effect in the summer when the direct solar radiation in Austin is the strongest. It should be noted here that 80% of the blinds were open during the occupied period (the daytime) and 80% are closed at night. This would not greatly reduce the solar gains into the building since most are opened during the daylight hours. The day-lighting is successful throughout the year (more greatly in the summer than the winter) and it surpasses the night-ventilation in energy efficiency in the spring and fall, perhaps because the daily temperature extremes are less during those times. The specific peak power differences on the heating, cooling, and systems loads are shown in the graphs in Figures 6-8. The majority of the systems loads are constant for all the cases but the difference is due to the varying fan and pumps power consumption levels for the cases. The lighting is included with the systems loads and is constant for all cases.

AUSTIN, TX vs. PHOENIX, AZ

All of these external parameters are utilized to maximize the energy efficiency in the optimized Austin thermal mass design and are compared with their use in the Austin baseline design and the optimized thermal mass design both in Austin, TX and in Phoenix, AZ (Figure 9). The Austin baseline model with all the extra parameters follows the optimal Austin model (also with those parameters) in the summertime but it performs about 1 kW worse in the winter, showing that even in this situation the thermal mass still has some beneficial use in Austin.

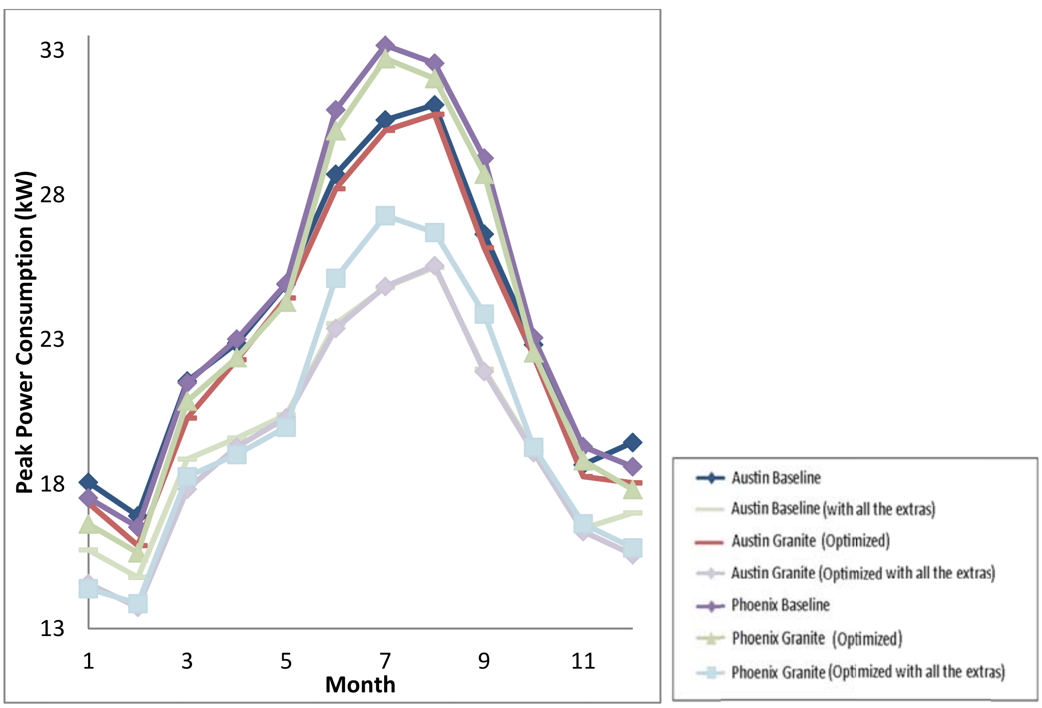

Figure 9: Comparing the optimized case and the baseline building in Austin and Phoenix and the case with the additional procedures to enhance thermal mass behavior.

In Phoenix the optimized Austin thermal mass design performs much worse overall, consuming a great deal more power (about 7.5 kW) in the summer but crossing over and doing slightly better than Austin in the winter (saving about 0.6 kW relative to the Austin case). The trend is the same for the baseline buildings in both cities and also once all the external variables have been added to both building model loads yet the difference in the winter is minimized for this. Overall the poorer performance of Phoenix is surprising because the literature so strongly promotes thermal mass benefits in hot-dry climates (like Phoenix) over hot-humid climates like Austin. The building has been optimized for Austin however, so one cannot expect to achieve as positive results when a building design is applied in a region other than where it was designed. The results for the external wall cases are shown below in Figure 10 for Phoenix and Austin. The optimum case in Austin with all the extra external parameters is better than that same situation in Phoenix except for during the springtime but the difference is pretty much negligible in the wintertime. All of the Austin cases with thermal mass have a greater difference (and more beneficial) from the corresponding cases in Phoenix in the summer but in the winter the Phoenix climate produces better results (though the difference is less). This actually confirms that a design that is optimal in one region or climate may not give the desired results in a different locale.

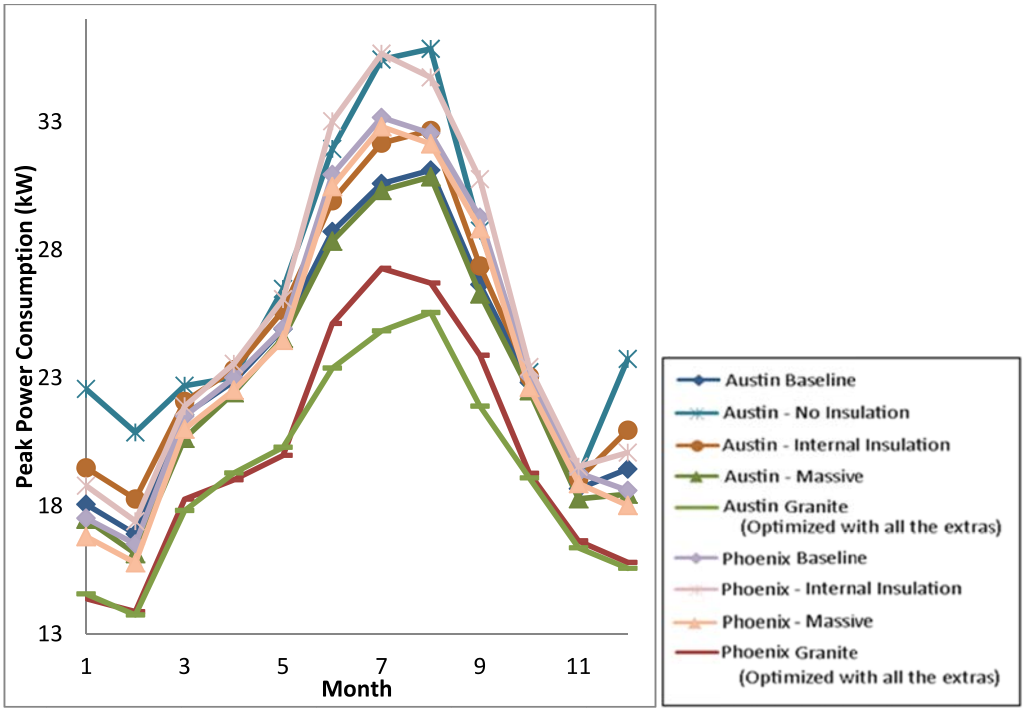

Figure 10: Comparison of the envelope cases in Austin and Phoenix showing how climates affect building performance.

In the Phoenix cases all the alternative materials models performed pretty much equivalently along with the geometry 5 and the ½ and 1.5 massive cases. The success expected in Phoenix was not seen in this study. Overall, Austin can benefit some from thermal mass use, especially if proper attention is paid to material properties, night ventilation and day-lighting. The baseline commercial building design can be improved greatly by incorporating day-lighting, night ventilation, and shading into the design. In the summer the electrical power consumption between the optimized Austin thermal mass design with the extras and the baseline with the extras is about the same, but in the winter there is still a large peak power savings in the thermal mass design. This shows the benefit of these additional techniques even on buildings without thermal mass but also it demonstrates the continued value of thermal mass in the wintertime. However, compared with the baseline case without the added external systems the thermal mass performs better overall whether including or not the additional systems.

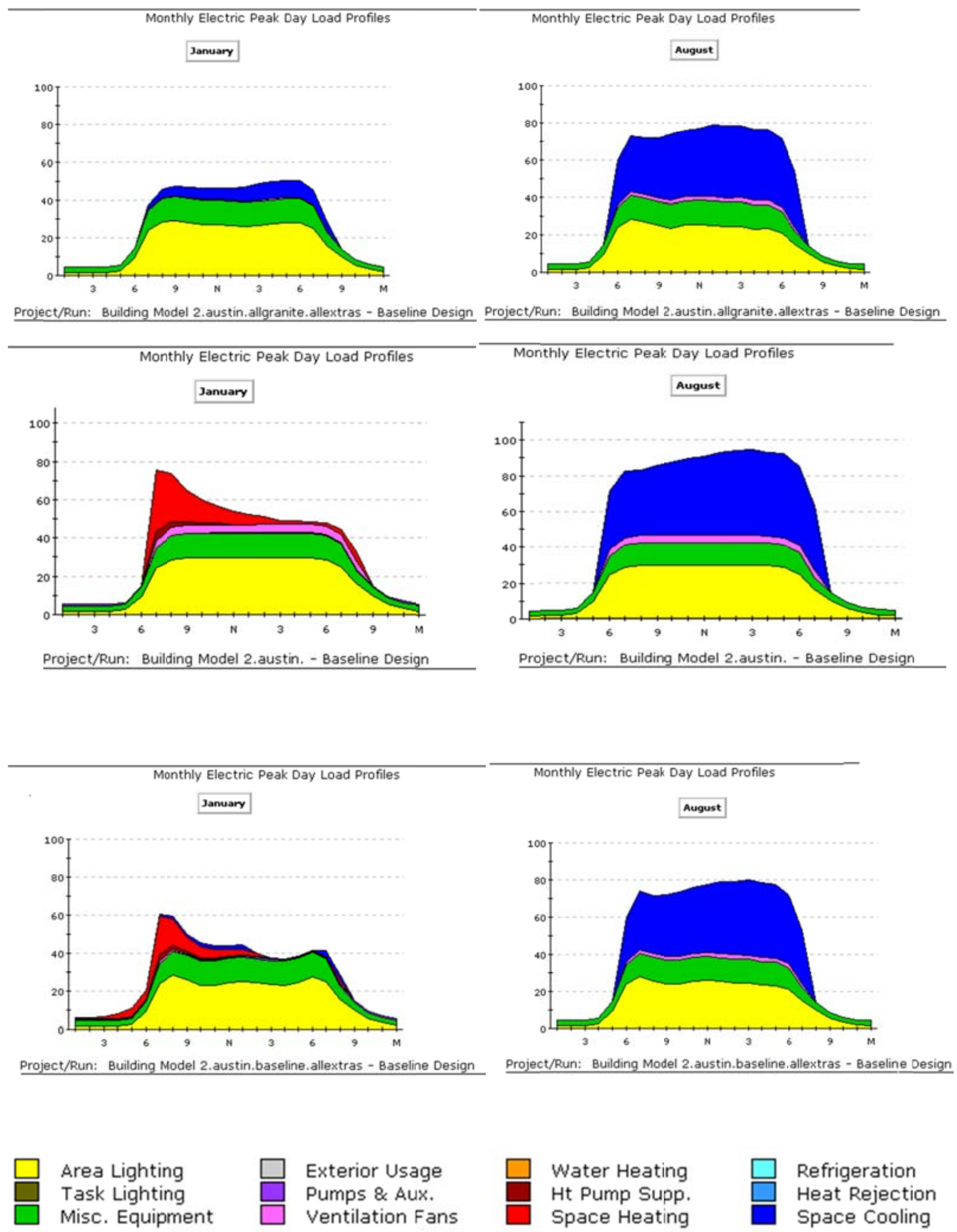

Figure 11: Comparison of the hourly power consumption for the average day in the months of January and August for three cases: the Austin baseline cases with and without the external parameters and the optimal thermal mass case with those parameters.

In Figure 11 a different picture is evident by looking at the monthly peak load profiles for January and August for three of the cases (the optimal Austin thermal mass design, the Austin baseline design and the baseline design with all the extra parameters). The thermal mass case is seen to sharply reduce the amount of heating electrical power consumed in winter in the early morning but the evening temperature is about the same, if not higher than both baseline cases. The loads however, are largely cooling, even in the winter, for the thermal mass building with the extra systems active. The baseline case with all the extras seems to exhibit a slight spike around noontime where there is a dip in the electrical power consumption of the optimized thermal mass case. The models with the extra parameters should have the same lighting distribution throughout the day for each month but this appears not to be true in January. The case without day-lighting has slightly different lighting usage levels because of the occupational use of the building. When the extra parameters are added the ventilation and fan loads decrease in the graphs. The August cooling loads look very similar throughout the day between the optimized case and the baseline (with all the extras) but the optimized case appears to be slightly lower. It is possible that the thermal mass yields a difference in August that is not as profound as anticipated because the daily air temperature swing in August in Austin is less because it is hot all the time. However the sun beating on the external walls of the building can add extreme heat energy during the day.

SUMMARY

Overall the literature has described the properties and uses of thermal mass and presented many views about its potential in different situations. It has been shown that though many authors recommended against utilizing thermal inertia in hot-humid regions like Austin, TX some benefit to its use can actually be found. Through eQUEST the thermal mass can be seen to successfully save power in Austin compared with a baseline standard commercial building in the area. Not only that but it has saved more peak power than the same thermal mass building in Phoenix, AZ. This is likely because the building was designed for the Austin region and not Phoenix but it is surprising nonetheless. The peak power savings associated with the thermal mass is mainly in relation to the heating and cooling loads of the building. In some cases the thermal mass building has tended to use more power in the pumps, fans, and auxiliary systems of the building but these costs are outweighed by the savings in the other conditioning loads. The overall power consumption can be reduced very effectively by the implementation of the day-lighting or night-cooling in conjunction with the thermal mass as these allow for the massive material to store up and to release heat energy more efficiently. There can be very large benefits for using these techniques in a standard building without thermal mass; however the building performance can be optimized by combining the two. The "green" technology of thermal inertia does have use in Austin where it can make a difference environmentally by reducing power consumption and monetarily by saving in electricity costs associated with thermal mass. Reducing cost can be a big selling point for commercial buildings and since it also reduces overall electrical power consumption then it is an incentive to care about the environment. This cost savings is what will get people's attention initially but it is the energy savings that make thermal inertia a sustainable option that will continue to be employed as it has throughout history when designed properly.

FUTURE WORK

There is potential for future research to investigate the cost versus the benefit analysis involved with incorporating more thermal mass into an actual commercial building design in Austin, TX. The benefits have been established in this paper but the specific costs and payback period have yet to be ascertained because it depends on the exact materials selected, the way they are implemented, and the way the building is operated. The specific material can be selected using dynamic properties approaching that of the granite material with attention to material cost and practicality. Because all of the thermally massive thickness and geometry models in this study had similar electrical power consumption results there is leeway in optimizing the building geometry to minimize cost without greatly affecting power consumption. Attention can also be paid to use of local materials (perhaps limestone) and the embodied energy in building materials. This should also include the operational and initial costs associated with night ventilation and day-lighting.

WORKS CITED

Al-Homoud, M. (2005). Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment, 40,* 353-366.

Al-Homoud, M., & Abdou, A., & Budaiwi, I. (2009). Assessment of monitored energy use and thermal comfort conditions in mosques in hot-humid climates. *Energy and Buildings, 41,* 607-614.

Al-Turki, A.M., & Gari, H.N., & Zaki, G.M. (1997). Comparative study on reduction of cooling loads by roof gravel cover. *Energy and Buildings, 25,* 1-5.

Andreasi, W.A., & Lamberts, R., & Cândido, C. (2010). Thermal acceptability assessment in buildings located in hot and humid regions in Brazil. *Building and Environments, 45,* 1225-1232.

Anselm, A.J. (2008). Passive annual heat storage principles in earth sheltered housing, a supplementary energy saving system in residential housing. *Energy and Buildings, 40,* 1214-1219.

Arnold, D. (1999, October). Building mass cooling—case study of alternative slab cooling strategies. CIBSE National Conference, Harrogate, UK. (Cited in Russell and Surendran, 2001)

Aste, N., & Angelotti, A., & Buzzetti, M. (2009). The influence of the external walls thermal inertia on the energy performance of well insulated buildings. *Energy and Buildings, 41,* 1181-1187.

Barmpas, F., & Bouris, D., & Moussiopoulos, N. (2009). 3D Numerical Simulation of the Transient Thermal Behavior of a Simplified Building Envelope Under External Flow. *Journal of Solar Energy Engineering, 131,* 1-12.

Burch, D., & Johns, W., & Jacobsen, T., & Walton, G., & Reeve, C. (1984). The effect of thermal mass on night temperature setback savings, *ASHRAE Trans., 90 (2A),* 184–206. (Cited in Ogoli, 2003)

Chiras, D.D. (2002). *The solar house: passive heating and cooling.* Canada: Chelsea Green Publishing Company.

US DOE-Energy Efficiency and Renewable Energy (US DOE), (2009). *2009 Buildings Energy Data Book*. D&R International, Ltd. Available from: http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2009_BEDB_Updat d.pdf.

US DOE-Energy Information Administration, (2003). *(CBECS) Overview of Commercial Buildings, 2003.* Available from: http://www.eia.doe.gov/emeu/cbecs/cbecs2003/overview.pdf.

US DOE-Energy Information Administration, (2010). International Energy Outlook 2010 – Highlights, DOE/EIA-0484. Available from: http://www.eia.doe.gov/oiaf/ieo/highlights.html.

Drysdale, J. (1976). *Technical Study No. 27.* Comm. Exp. Bldg. Station, Australia. (Cited in Ogoli, 2003)

(2007). *eQUEST Modeling Procedures Quick Reference Guide*. Camarillo, CA: James J Hirsch and Associates.

Farouki, O. T. (1981). *Thermal properties of soils*, CRREL Cold Regions Research and Engineering Laboratory Monograph 81-1, U.S. Army Corps of Engineers, Hanover, NH. (Cited in Marra, 2006)

Fathy, H. (1973). *Architect for the Poor*. Chicago, IL: University of Chicago Press. (Cited in Ogoli, 2003)

Freitag, D. R., & McFadden, T. (1997). *Introduction to cold regions engineering.* USA: American Society of Civil Engineers. (Cited in Marra, 2006)

Gregory, K., & Moghtaderi, B., & Sugo, H., & Page, A. (2008). Effect of thermal mass on the thermal performance of various Australian residential constructions systems. *Energy and Buildings, 40,* 459-465.

Hacker, J.N., & De Saulles, T.P., & Minson, A.J., & Holmes, M.J. (2008). Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate. *Energy and Buildings, 40,* 375-384.

Hasnain, S.M. (1998). Review on Sustainable Thermal Energy Storage Technologies, Part 1: Heat Storage Materials and Technologies. *Energy Conversion and Management, 39 (11),* 1127-1138.

Henze, G.P. (2005). Energy and Cost Minimal Control of Active and Passive Building Thermal Storage Inventory. *Journal of Solar Energy Engineering, 127,* 343 351.

Henze, G.P., & Le, T.H., & Florita, A.R., & Felsmann, C. (2007). Sensitivity Analysis of Optimal Building Thermal Mass Control. *Journal of Solar Energy Engineering, 2007, 129*, 473-485.

Huberman, N. & Pearlmutter, D. (2008). A life-cycle energy analysis of building materials in the Negev desert. *Energy and Buildings, 40,* 837-848.

Labs, K. (1979). Underground building climate. *Solar Age, 4(10),* 44-50. (Cited in Anselm, 2008)

Langston, C.A., & Ding, G.K.C. (2001). *Sustainable Practices in the Built Environment (2nd ed.)*. Oxford, UK: Butterworth Heinemann. (Cited in Huberman and Pearlmutter, 2008)

Marra, W.A. (2006). Heat Flow through Soils and Effects on Thermal Storage Cycle in High-Mass Structures. *Journal of Aerospace Engineering, 19 (1),* 55-58.

Milne, G., & Reardon, C. (2004). *Materials Use: 3.1-Embodied Energy*. Australia, 2004. Available from: http://www.greenhouse.gov.au/yourhome/technical/fs31. (Cited in Huberman and Pearlmutter, 2008)

Nagano, K., & Takeda, S., & Mochida, T., & Shimakura, K., & Nakamura, T. (2006). Study of a floor supply air conditioning system using granular phase change material to augment building mass thermal storage—Heat response in small scale experiments. *Energy and Buildings, 38 (5),* (436-446).

Oakridge National Laboratory, (2002). *Insulation fact sheet with addendum on moisture control*. DOE/CE-0180 (US DOE-EREE), Oakridge, TN. (Cited in Al Homoud, 2005)

Oakridge National Laboratory, (2008). *Insulation fact sheet.* DOE/CE 0180 (US DOE-EREE), Oakridge, TN. Available from: http://www.ornl.gov/~roofs/Zip/tmp/results24049.html.

Ogoli, D.M. (2003). Predicting indoor temperatures in closed buildings with high thermal mass. *Energy and Buildings, 35*, 851-862.

Palmer, J.M., & Curtis, S.G., & Pane, W. (2005). Thermal Mass in Buildings—Practical Issues with Concrete Construction, CTU Congress, Dundee, UK. (Cited in Hacker et al., 2008)

Raychaudhury, B.C., & Chadhury, N.K.D. (1961, November). Thermal performance of dwelling in the tropics, in: Proceedings of the Symposium on the Functional Efficiency of Buildings, CBRI. (Cited in Ogoli, 2003)

Russell, M.B., & Surendran, P.N. (2001). Influence of active heat sinks on fabric thermal storage in building mass. *Applied Energy, 70,* 17-33.

Szokolay, S.V. (2008). *Introduction to architectural science: the basis of sustainable design (2nd ed.).* Burlington, MA: Elsevier Ltd.

Taylor, P., & Luther, M.B. (2004). Evaluating rammed earth walls: a case study. *Solar Energy, 76,* 79-84.

Thomas, J. M., & Algohary, S., & Hammad, F., & Soboyejo, W.O. (2004). Materials selection for thermal comfort in passive solar buildings. *Journal of Materials Science, 41 (21),* 6897-6907.

Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and Environment, 37*, 429–435. (Cited in Huberman and Pearlmutter, 2008)

Upadhyay, A.K. (2008, February). *Thermal Mass Requirement for Building Envelope in Different Climatic Conditions*. 14th International Brick &Block Masonry Conference 2008, Sydney, Australia.

Yan, Z., & Lam, J.C., & Liu, J. (2005). Experimental Studies on the Thermal and Moisture Properties of Rammed Earth Used in Adobe Buildings in China. *Architectural Science Review, 48 (1)*, 55-60.

Yilmaz, Z. (2007). Evaluation of energy efficient design strategies for different climatic zones: Comparison of thermal performance of buildings in temperate-humid and hot-dry climate. *Energy and Buildings, 39,* 306-316.

Zhang, Z.L., & Wachenfeldt, B.J. (2009). Numerical study on the heat storing capacity of concrete walls with air cavities. *Energy and Building, 41,* 769-773.

Zhu, L., & Hurt, R., & Correa, D., & Boehm, R. (2009). Comprehensive energy and economic analyses on a zero energy house versus a conventional house. *Energy, 34,* 1043-1053.

VITA

Mariel Elizabeth Kerbacher was born in San Antonio, Texas. After completing her work at Fairfield High School, Fairfield, Texas in 2004, she entered Southwestern University in Georgetown, Texas where she received the degree of Bachelor of Arts in May, 2008. After a year out of school traveling and working self-employed as a tutor, substitute teacher and designer, in September, 2009, she entered the Graduate School at The University of Texas at Austin.

Permanent Address: 202 Private Rd. 1280
Fairfield, Texas 75840
Mkerbacher@gmail.com

This report was typed by the author.